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Guidelines for Mapping Areas at Risk of Landslides in Europe

Proceedings of the Experts Meeting held on 23-24 October 2007
Institute for Environment and Sustainability
Joint Research Centre (JRC), Ispra, Italy

Edited by Javier Hervás

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The mission of the JRC-IES is to provide scientific-technical support to the European Union's policies for the protection and sustainable development of the European and global environment.

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Preface

Landslides are complex phenomena that affect urban settlements, infrastructure and agricultural and environmentally valuable land in many sloping areas in Europe. Nowadays, landslide risk is substantially increasing in these areas as a result of growing urbanization and associated infrastructure together with increasing or changing precipitation trends.

In 2006, the European Commission adopted the Thematic Strategy for Soil Protection, from which it derived a Proposal for a Soil Framework Directive which is now under discussion at EU Council and Parliament levels. This legislative framework includes landslides among the various soil threats for which it is proposed to establish national programmes in EU member states, first to identify the areas at risk of these threats or hazards using common approaches and elements and then to set up mitigation measures to reduce the risk and preserve soil functions.

It is generally recognised that mapping landslide distribution (i.e. inventorying) and susceptibility (basically "where" landslides may occur in the future), hazard (basically "where and when or how often") and risk (potential damage or losses) are challenging tasks. In Europe, geological, morphological and other geo-environmental settings and conditions are greatly variable, as are the main natural landslide triggers (e.g. rainfall, seismicity and rapid snowmelt). In addition, landslide mapping has not been coped with the same effort or using the same approach both across and within EU member states. As a result, there is a lack of harmonisation of mapping approaches and models, input data to them, and susceptibility, hazard and risk representation levels and scales in Europe. Hence, existing landslide-related maps greatly differ between countries and often as well between regions within the same country.

In this context, the Joint Research Centre (JRC) of the European Commission, as part of its soil research programme, has set up a landslide experts group to provide scientific and technical support to JRC in its endeavour to scientifically assist the landslide-related soil policy making process at EU level. This group, which is open to further membership, initially includes representatives from a number of national geological surveys, research institutes and universities in Europe.

A first meeting of the experts group was held at JRC in Ispra, Italy, on 23-24 October 2007 with the main aim to exchange information on landslide inventories, susceptibility, hazard and risk mapping approaches and programmes in a number of member states and, especially, to discuss and draft basic guidelines for a common approach for mapping areas at risk of landslides in Europe.

This volume presents the results of the above-mentioned meeting. First, pan-European soil and land-cover spatial databases as well as issues concerning landslide mapping harmonisation in EU member states are introduced. Then, national and regional landslide inventory programmes and other mapping initiatives in Great Britain, Italy, Greece and southern Spain are reported. Subsequently, landslide susceptibility, hazard and risk assessment and mapping approaches and programmes in some major mountain regions and Tertiary sedimentary basins of Spain, Italy and France are discussed. This first block of short papers ends with the presentation of main criteria for identification of European landslide risk areas based on geographically nested "Tier" approaches, taking as reference examples from Germany and Italy. Finally, a set of recommendations for harmonised mapping of landslide-prone areas in Europe is given. These include the use of multi-step "Tier" approaches at various scales: from Europe-wide susceptibility mapping at small scale using common, readily available data on conditioning and triggering factors related to landsliding, to medium-scale mapping of areas identified in the previous step as highly susceptible to landslides, by applying statistical approaches using also available landslide inventory data, and to large-scale mapping in high-susceptibility/hazard local areas. For the latter, use of physically-based models is recommended.

It should be noted that other aspects of landslide map harmonisation, such as data exchange formats, metadata, user accessibility, etc., have not yet been dealt with by the landslide experts group. As they form part of the INSPIRE Directive concerning spatial data infrastructures in Europe, it is envisaged to coordinate these issues with the thematic groups that are being established to implement this Directive.

Pan-European soil databases

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The European Soil Portal and the European Soil Database

The European Soil Portal is the joint contribution of the European Commission and the European Soil Bureau Network (ESBN) to the building of a thematic spatial data infrastructure for soils. This portal, located at http://eusoils.jrc.ec.europa.eu/, is the place in which all relevant data and information regarding soils at European level has been collected. Furthermore it is a useful utility for the ESBN to promote its range of activities. The activities related to this portal are in line with activities related to the INSPIRE Directive (Infrastructure for Spatial Information in Europe). INSPIRE deals, among others, with difficulties to identify, access and use available spatial information in Europe.

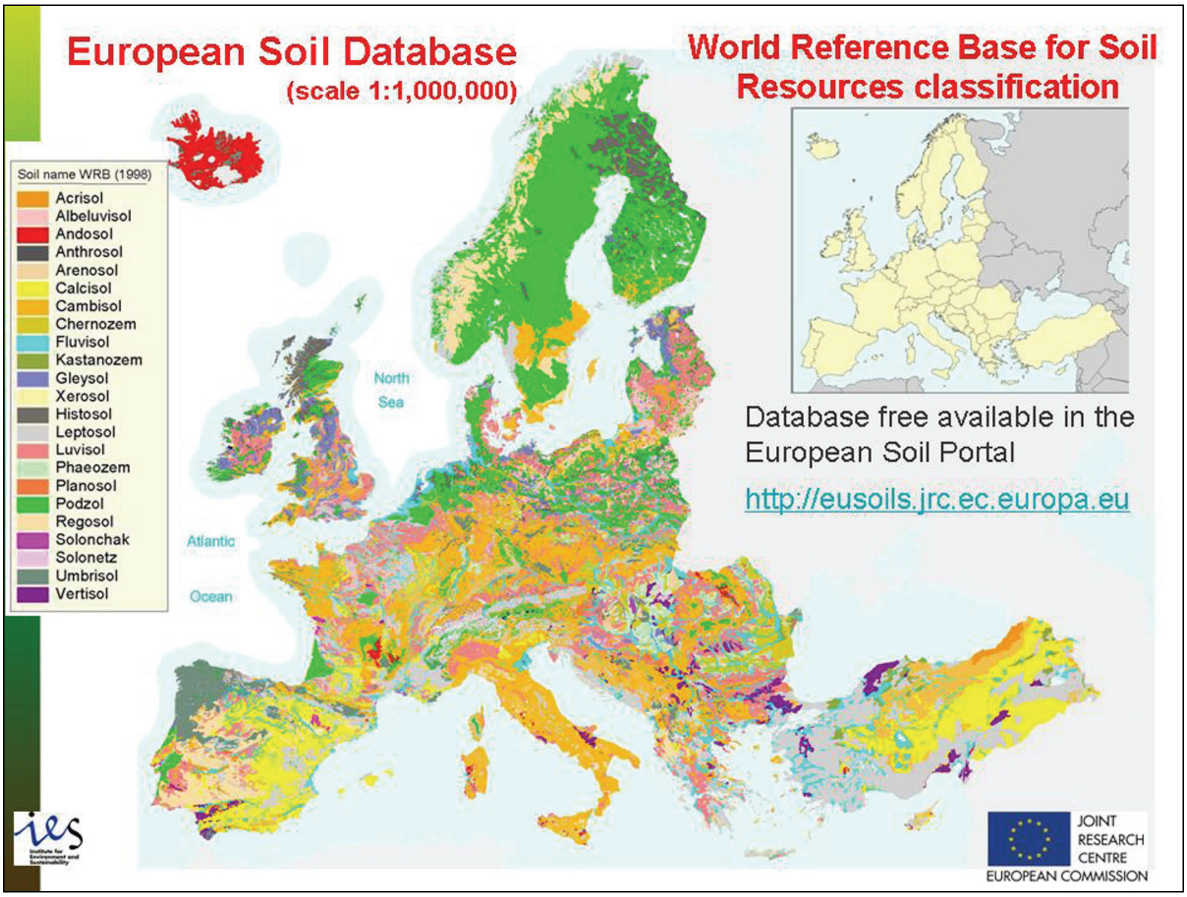

Figure 1: World Reference Base (WRB) Classification in the European Soil Database.

The European Soil Portal has been considered as a success story of networking different soil information at European level. It is mainly built around the European Soil Database (ESDB), which consists of a number of components of which the Soil Geographical Database of Eurasia (SGDBE) at Scale 1:1,000,000 is one.

The European Soil Database structure and the data distribution

The European Soil Database (ESDB) contains a list of Soil Typological Units (STU). Besides the soil names they represent, these units are described by variables (attributes) specifying the nature and properties of the soils: for example the texture, the water regime, the stoniness, etc. The geographical representation was chosen at a scale corresponding to the 1:1,000,000. At this scale, it is not feasible to delineate the STUs. Therefore they are grouped into Soil Mapping Units (SMU) to form soil associations and to illustrate the functioning of pedological systems within the landscapes (see Fig. 2). One of the 73 attributes in the European Soil Database is the Dominant Parent Material for the STU (see Fig. 3).

The European Soil Database (ESDB) is the main source of information from which most other data information and services are derived. For instance, the "European Soil Database v2 Raster Library" contains raster (grid) data files with cell sizes of both 1km x 1km and 10km x 10km for a large number of soil related parameters. The 10km x 10km rasters are in the public domain access and allow expert users to use the data for instance to run soil, water and air related models. The 1km x 1km rasters are available after a prior registration. The grids fit with ideas from INSPIRE to develop "nested" systems for reporting and updating European soil data at different scales, according to a hierarchy of grids with a common point of origin and standardized location and size of grid cells. The European Soil Portal provides the full documentation of all components of the ESDB.

The soil data files are accompanied by as many static soil maps, which allow the user to have a quick overview of the distribution of soil characteristics in a spatial way. The World Reference Group (WRB) map (Fig. 1) is a representative static soil map produced from the ESDB.

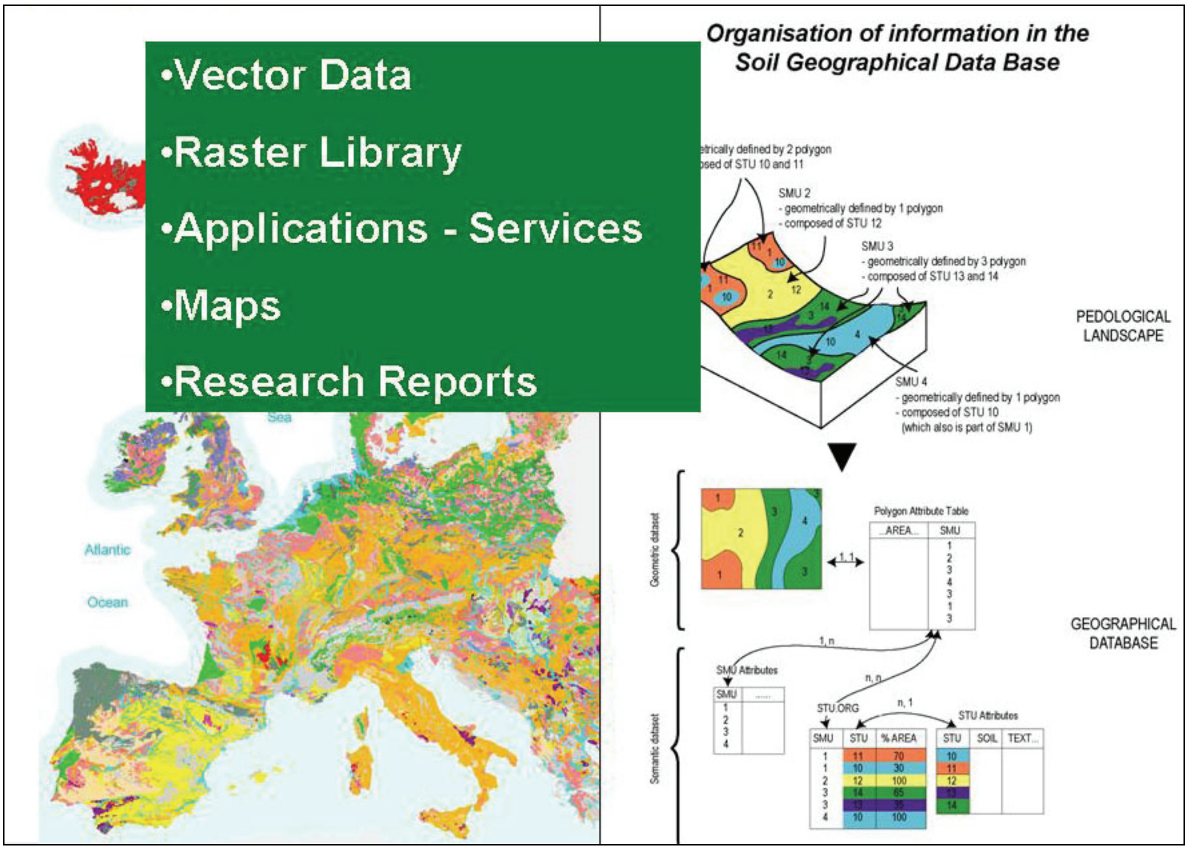

Figure 2: The structure of the European Soil Database.

Additionally, a number of mapping services have been developed in order to allow the general public to navigate and query soil data. The SOMIS (SOil Map Internet Service) is a web-based application for the navigation of ESDB related data through a map interface.

European Soil Data Centre and support to EU policies

The European Soil Data Centre (ESDAC) is the thematic centre for soil related data in Europe and has been established according to a decision taken at the end of 2005 by the European Commission's DG ENV, DG JRC, ESTAT and the European Environment Agency (the so-called "group of four" or G04) to establish ten environmental data centres in Europe.

The European Soil Data Centre (ESDAC) hosts soil related products: datasets, documents, services and other types of information such as maps and graphs and provides web-based tools for the access to and the update of its contents.

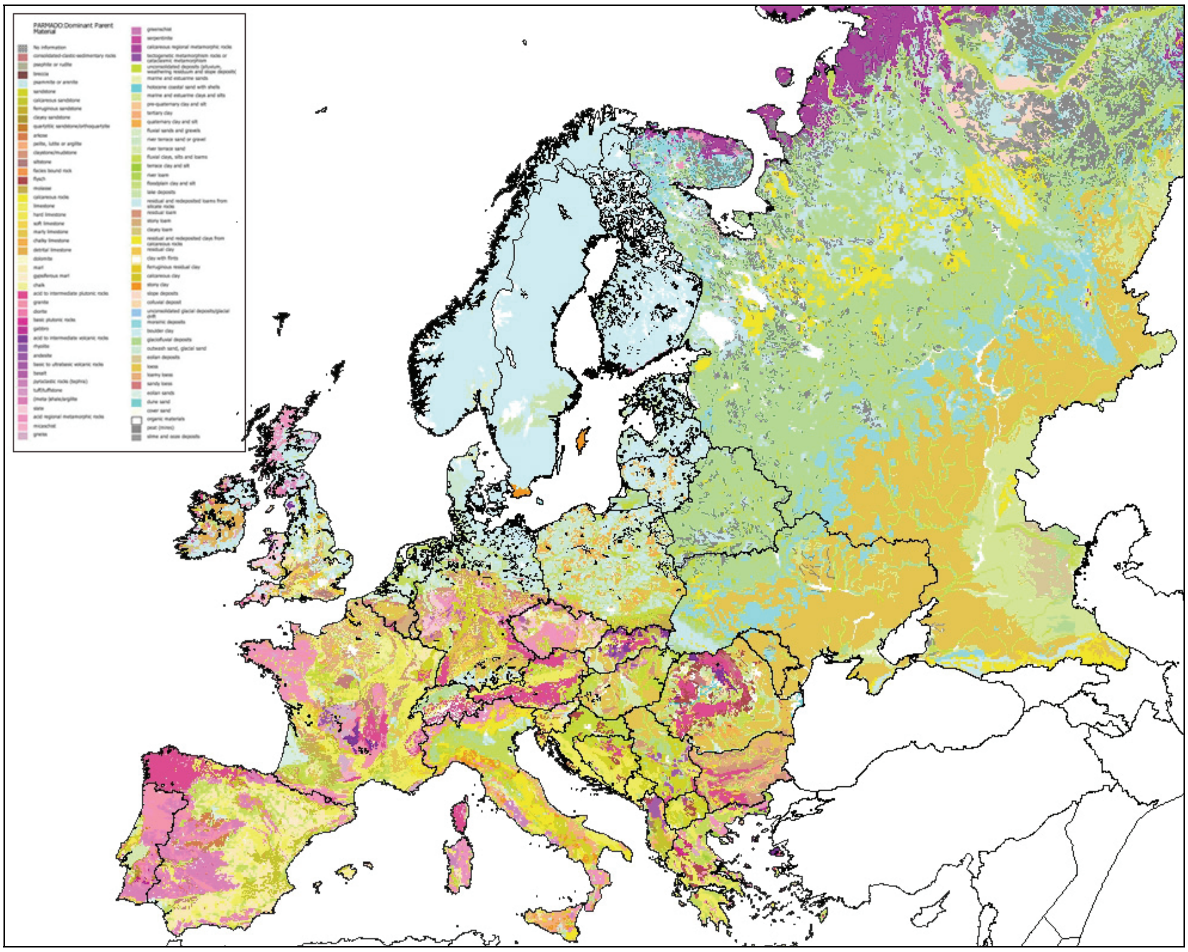

Figure 3: Dominant parent material code of the Soil Typological Unit.

Among the others, ESDAC hosts data related to Soil Erosion Estimates and Soil Organic Carbon Contents. The future objective is to host data related to the other Soil threats (Soil Compaction, Landslides, Soil Salinisation) as they are described in the proposal for a framework Directive (EC, 2006).

ESDAC is the most appropriate place to organise the data collection as:

- Data collection should be organized in an efficient way due to past experiences

- Necessary quality assurance will be performed
- All relevant data are accessible to policy makers and furthermore to European citizens
- Technical support will be provided including database issues, metadata standards and web development
- Staff has relative experience in data exchange format issues
- Integration with other datasets in ESDAC will derive added-value products.

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Main issues on landslide mapping harmonisation in EU member states in the framework of European Commission soil policy

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On 22 September 2006 the European Commission adopted the Thematic Strategy for Soil Protection. This legislative package included a communication on the mentioned Strategy (EC, 2006a), a proposal for a Soil Framework Directive (EC, 2006b) and the impact assessment of the Strategy (EC, 2006c). In this framework it is required, among other actions, to identify risk areas for several soil threats including landslides using common criteria and to establish a programme of measures to cope with them (Fig. 1 and Table 1).

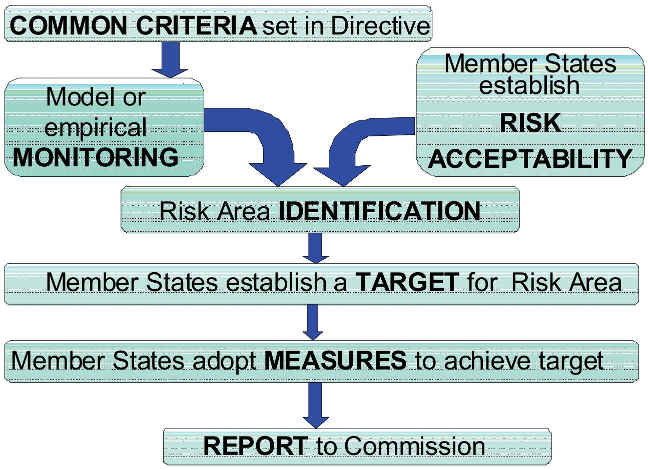

Figure 1: Approach suggested in the Soil Thematic Strategy to address erosion, organic matter decline, salinisation, compaction and landslides.

Table 1: Common elements or criteria for risk area identification according to soil threats, as included in Annex I of the Proposal for a Soil Framework Directive.

SECTION 5 COMMON ELEMENTS FOR THE IDENTIFICATION OF AREAS AT RISK OF LANDSLIDES
Soil typological unit (STU) (soil type)
Occurrence/density of existing landslides
Bedrock
Topography
Land cover
Land use (including land management, farming systems and forestry)
Climate
Seismic risk

In the proposal for a Soil Framework Directive, risk areas are understood as areas where one or more of the soil degradation processes mentioned in Fig. 1 have occurred or are likely to occur in the near future. In this context, identification of landslide risk areas could in principle be accomplished by one or more of the following maps.

- Landslide inventory maps (and landslide density maps as a by-product), which show at least the geographical distribution of past landslides, and associated database of landslide and terrain properties.
- Landslide susceptibility maps, which show the proneness or the probability of occurrence of landslides of certain type in a given area.
- Landslide hazard maps, which show the probability of occurrence of landslides of certain type and magnitude in a particular area within a given period of time.
- Landslide risk maps, which show potential damage or losses caused by landslides to individuals, infrastructure and property.

Landslide susceptibility, hazard and risk maps are often referred to as landslide zonation (or zoning) maps. Landslide susceptibility maps are the most common. They can be produced through analysis of geo-environmental parameters related to slope instability and landslide inventory data (see e.g. the "common elements" in Table 1).

Approaches and models for landslide susceptibility assessment can be classified for instance as qualitative and quantitative. Qualitative methods include direct susceptibility mapping (also called geomorphological mapping), which is based mainly on aerial photo-interpretation and field surveys, and indirect susceptibility mapping, based mainly on weighting of parameter maps and classes within the maps. Qualitative landslide susceptibility maps can be produced at any scale. These maps can sometimes be very useful, especially when landslide inventories are not available, although they are difficult to compare as they are based on expert judgement.

Quantitative models for landslide susceptibility assessment and mapping include mainly statistical and physically-based models. Statistical models combine detailed information on past landslide occurrence and a set of geo-environmental parameters and provide relative weighting values for the parameters selected.

Physically-based models are based on slope stability analysis and provide mainly safety factors. They usually require slope, geomechanical and groundwater data, as well as peak ground acceleration (PGA) data in seismic areas. Maps using statistical or physically-based models are easier to compare, although both types of models need thematic data which are often not readily available, especially those to be used in physically-based models. Statistical modelling is generally suitable for mapping landslide susceptibility at various scales, especially at medium (regional) scale. Physically-based modelling however is mainly suitable for large-scale (local) mapping.

Hazard mapping needs geo-environmental parameter data and landslide inventories including landslide spatial distribution and timing/frequency information (ideally historical data of first-time landslide occurrence and reactivations).

Landslide risk mapping in turn needs information on landslide hazard, amount and value of elements at risk (i.e. exposure) and vulnerability of these elements (i.e. degree of loss). Risk can be qualitatively or quantitatively evaluated, as well as separately estimated for individuals and property/infrastructure. It should be noted that quantitative risk assessment (QRA) requires collecting comprehensive data that may not be available in many areas.

Other possible landslide zonation maps are density maps. These are based on landslide inventories and expert-selected mapping units. Such maps however do not specifically show where landslides may occur in the future.

In harmonised landslide-related mapping it is necessary to consider a number of issues. In addition to using common terrain or geo-environmental landslide factors (e.g. the "common elements" in the proposed Directive as they are now or further reviewed) and common mapping approaches and models, it would be necessary to use common representation scale(s), mapping units, a common landslide classification, common map symbology including same susceptibility, hazard or risk descriptive classes, etc. Additionally, differences in geomorphological, climatic and seismicity conditions and data availability both between and within EU member states should be born in mind.

With regard to the mapping scale(s) there are several possibilities depending on the area covered by the map (e.g. minimum 1:1,000,000 scale for European- and nation-wide small-scale mapping), or on the landslide density and population/infrastructure density (e.g. minimum 1:25,000 scale). Mapping scale is further dealt with elsewhere in this volume.

Particular attention should also be paid to the landslide classification in inventory maps and landslide potential maps. The various possibilities are briefly analysed in Table 2.

Table 2: Analysis of landslide classification criteria.

Common landslide classification criteria	Remarks
Type of movement and main material involved (e.g. Cruden and Varnes, 1996; Dikau et al., 1996)	• Ideal but complex to determine • Evidence not always clear without in-depth investigations • Compatibility problems between many existing maps • More appropriate for medium to large scale landslide inventory and zonation maps
Main type of movement (e.g. slide, flow, fall, complex), with or without specifying main material involved	• Somehow simplistic but practical at small scales (e.g. administrative regions or nation-wide)
Depth of sliding surface (e.g. shallow vs. deep-seated landslides)	• Imprecise determination in quick surveys • Suitable for very small scales (e.g. nation-wide)
Speed (e.g. fast vs. slow moving landslides)	• Subjective speed threshold • Difficult to determine for many old landslides • Suitable mainly for early warning and civil protection intervention
State of activity (e.g. active, dormant and relict, or active and inactive)	• Suitable but sometimes difficult to determine without in-depth investigations (e.g. analysis of historical records, remote sensing and field instrumentation techniques)
Combination of several of the above-mentioned criteria	• Suitable but some redundancy could be expected depending on the combined classification criteria selected

Last but not least, data formats and data accessibility must also be taken into consideration. Here it is important to use a common metadata standard and common data exchange formats for integration of new maps at European level. Issues such as use of open source map formats versus *de facto* commercial standards (e.g. ESRI's), feasibility of integration of landslide databases currently available in member states and integration of landslide zonation maps with maps for other soil threats regarded in the Directive proposal should also be investigated. In addition, some map standards and accessibility services should comply with the INSPIRE Directive (EC, 2007).

In this overall context, the JRC is committed to provide scientific and technical support to the European Commission's DG Environment and other relevant Commission Services (e.g. DG Research and others) on landslide related issues concerning the EU Soil Thematic Strategy and the associated Proposal for a Framework Directive. The creation, coordination and active contribution to the work of a European landslide expert group represent the main step to achieve this goal. The production of the present volume is the first result of this endeavour.

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BGS landslide data and mapping in Britain

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The variability of landslide types and scales in Britain matches that of the geology. Whilst Britain has some large active landslides (Fig. 1), it has also been affected in terms of loss of life by very small landslides (Fig. 2). This reflects the dense population and infrastructure of the country, and widespread public access.

Figure 1: Large landslide in Cretaceous chalk and mudstone at Folkestone Warren, Kent.

Figure 2: Small, yet fatal, landslide in glacial tills at Nefyn, North Wales.

National Geohazard Databases, including the landslide database, have been developed at the British Geological Survey (BGS) since 2000 (Culshaw, 2005). The map (Fig. 3) shows the current distribution of landslides in Britain for which data are available in the database. The database currently contains 14,500 entries, which are added to at a rate of about 1000 per year. These represent individual landslides, but for a small number of cases also include multiple events within the same landslide. In addition to the development of the database, landslide research is actively pursued at BGS in collaboration with universities and other institutes. Particular interest has recently been taken in the mechanisms of cambering, and in the problems associated with landslide mapping at the coast and in the urban environment (see Fig. 5). The development of a national digital geology map at 1:50,000 scale (DigMap50) has allowed the production of a commercial geohazard information system called 'GeoSure' (Harrison and Forster, 2006; Culshaw, 2007). This system includes seven geohazards: swell-shrink, mass movement, dissolution, compressible soils, collapsible soils, running sands and abandoned mineworkings. The system classifies the geological formations of Britain in terms of their susceptibility to each of these geohazards. The resulting output can then be used by the insurance industry and by the public, for example for buying and selling of property. In GeoSure, landslide susceptibility is assessed in 5 classes of natural slope, based on attribution of over 9,000 geological formations, combined with slope angle classification based on NextMap and re-gridded to 50m. Expert comparison of the National Landslide Database and GeoSure enables validation of the latter and allows mapping decisions to be made, particularly in areas where the landslide database is sparsely populated.

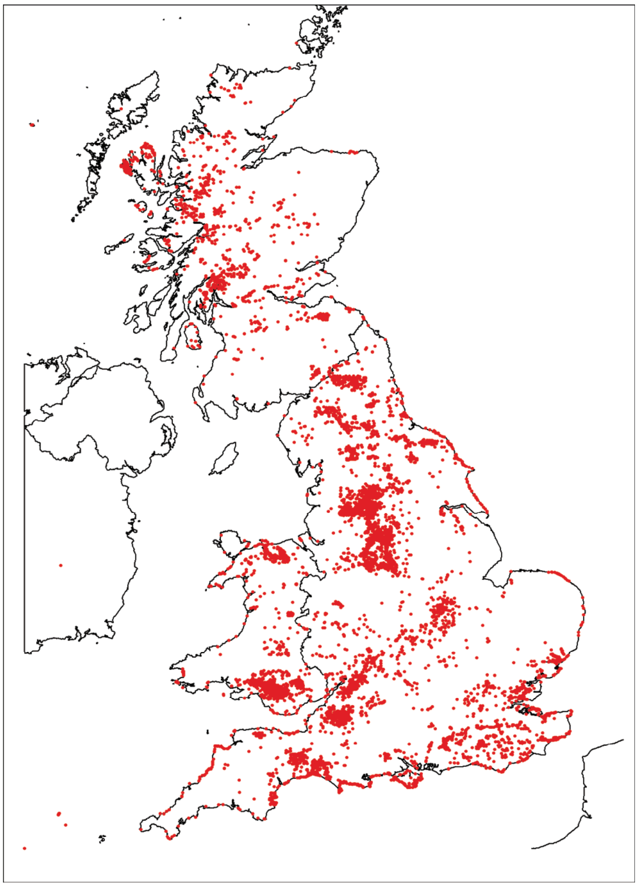

Figure 3: BGS's National Geohazard Databases – Landslides.

Mapping of landslides, and the continued population and upgrading of the database, has involved training BGS geologists in landslide recognition and recording, and has utilised digital field recording technology. A digital pro-forma is used (Fig. 4). In two pages, this covers the subjects of location, shape, mechanism, cause, slope, damage, and geology. In addition, freehand notes and references to the source of information may be added. In practice, many of these categories cannot be completed due to lack of information, particularly where the record is new. Hopefully, many can be revisited and completed at a later date as information becomes available.

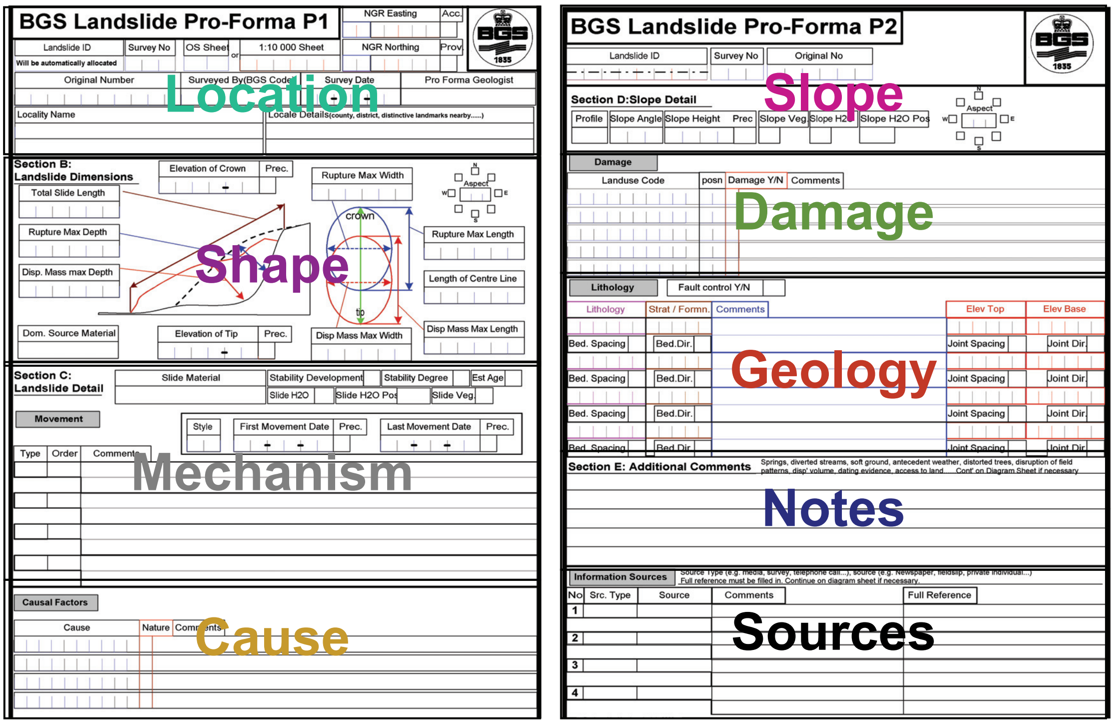

Figure 4: BGS's landslide mapping pro-forma showing data categories.

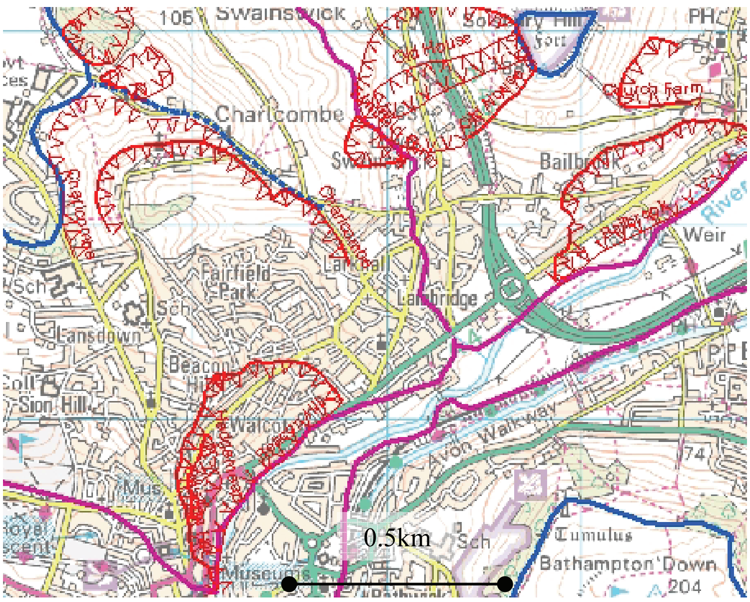

Figure 5: Part of an urban landslide map of Bath, Avon. The figure shows relict landslide backscarps and toes (red) and geographical features (blue, purple).

In recent years, landslide mapping projects carried out by BGS in Britain have involved several conurbations. An example is the city of Bath in the county of Avon (Fig. 5) where numerous relict landslide and cambering features are found in Jurassic and Cretaceous mudrocks, limestones and sandstones. One particular challenge for mappers is how to show key geomorphological features such as landslide backscarps, cambering gulls, and 'landslides within landslides' on traditional geology maps where only 'deposits' are shown as polygons. Of course, the linework on specialised landslide maps and databases has to agree with that on geological map standards. This may be difficult to achieve, and highlights some of the problems encountered when attempting to merge or reconcile regional or thematic projects with national maps, and is one of the issues dealt with by the QA system in relation to landslides and other geohazards. Landslide mapping and the Geosure system also provide challenges at the coast in terms of event recording/mapping, coastal erosion, and slope angle classification.

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The IFFI Project (Italian Landslide Inventory): methodology and results

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The Italian Landslide Inventory (IFFI, *Inventario dei Fenomeni Franosi in Italia*) is a national project that aims at identifying and mapping landslides over the whole Italian territory, based on standardized criteria. The project has been financed in 1997 with 4.1 Mil. Euro by the Committee of Ministries for Land Protection, established by the Italian Government (Law No. 183/89).

The institutions involved in the IFFI Project are: a) APAT - Geological Survey of Italy/Land Protection and Georesources Department, with the task of organizing and coordinating the activities, developing the guidelines, verifying the data conformity, building up a national geo-database and a WebGIS; b) Regions and Autonomous Provinces, charged to collect historical documents and other archive data and map the areas affected by landslides.

The methodology applied to build up the Italian Landslide Inventory is based on aerial photo-interpretation, field surveys, collection of historical documents and archive data.

The main sources of information consulted to compile the IFFI database are: a) National projects (AVI - Inventory of information on sites historically affected by landslides and floods in Italy for the period 1918/2000; SCAI - Special project for the study of unstable towns; CARG - Geological map of Italy, scale 1:50,000); b) Landslide inventories by Regions, River Basin Authorities, research institutes and universities; c) River Basin plans (PAI - L. 267/98); d) Emergency Declarations (L. 225/92); e) National and local public archives; f) Scientific and technical papers and reports.

With the aim to homogenize and integrate the landslide data over the whole Italian territory, the IFFI Landslide Data Sheet (Amanti et al., 2001) has been defined on the basis of international classification standards: Recommendations of the International Association of Engineering Geology (IAEG, 1990), International Geotechnical Societies UNESCO Working Party on World Landslide Inventory (WP/WLI, 1990, 1991, 1993a, 1993b, 1994), International Union of Geological Sciences Working Group on Landslides (IUGS/WGL, 1995), and Cruden and Varnes (1996).

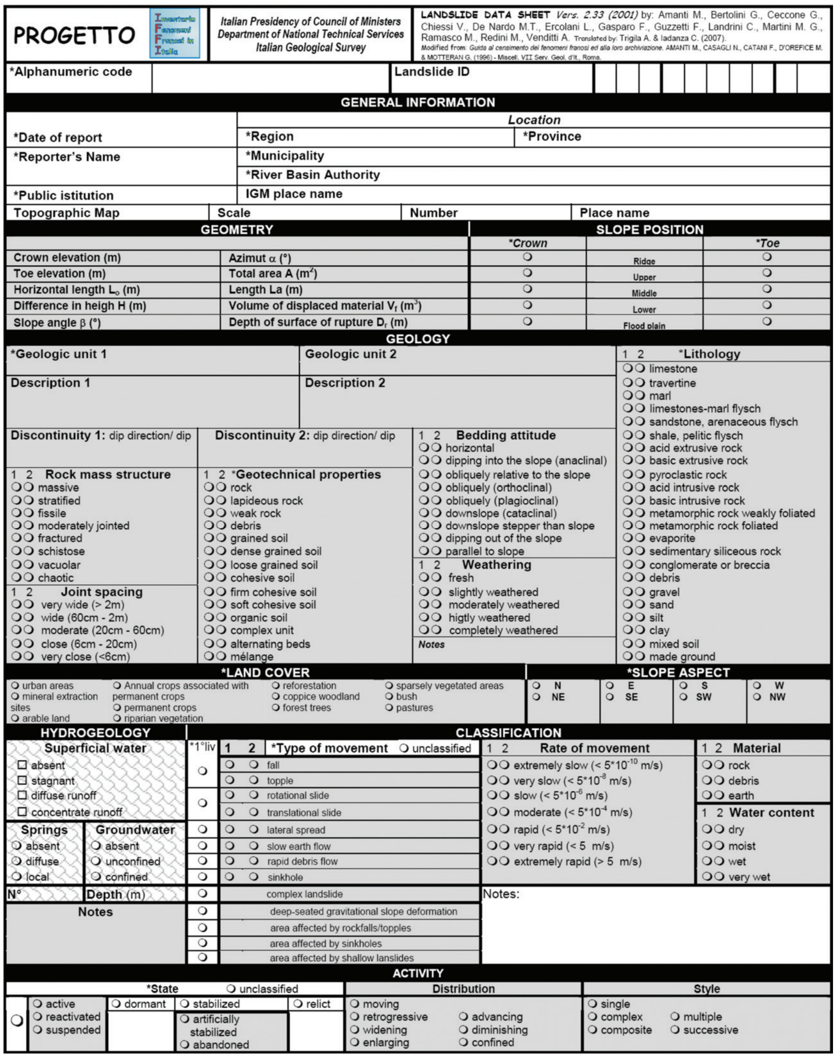
The IFFI Landslide Data Sheet (Fig. 1) is organised in three information levels of increasing detail:

- 1st level contains basic data on landslide location, type of movement and state of activity;
- 2nd level provides data on morphometry, geologic units, discontinuities, lithology, geotechnical properties, land use, causes of activation and date of activation;
- 3rd level gives detailed information on damages, investigation process and remedial measures for risk reduction.

The IFFI geo-database contains vector layers of landslides and an alphanumeric archive of attributes (RDBMS). The relational alphanumeric database scheme is based on the Landslide Data Sheet. The mapping scale is 1:10,000 for most of Italy. However, a smaller scale (1:25,000) has been used in mountain and sparsely populated areas.

Landslides are represented as:

- a georeferenced point, located at the highest point of the crown;
- a polygon, in case the landslide area is >10,000 m^2;
- a line, in case the width is too narrow and in case of debris flows.



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Department of National Technical Services
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*Alphanumeric code | Landslide ID

GENERAL INFORMATION

*Date of report | Location: *Region | *Province
*Reporter's Name | *Municipality
*River Basin Authority
*Public istitution | IGM place name
Topographic Map | Scale | Number | Place name

GEOMETRY

Crown elevation (m) | Azimut α (°)
Toe elevation (m) | Total area A (m^2)
Horizontal length L_o (m) | Length La (m)
Difference in heigh H (m) | Volume of displaced material V_f (m^3)
Slope angle β (°) | Depth of surface of rupture D_r (m)

SLOPE POSITION

*Crown | | *Toe
Ridge, Upper, Middle, Lower, Flood plain

GEOLOGY

*Geologic unit 1 | Geologic unit 2
Description 1 | Description 2
Discontinuity 1: dip direction/ dip | Discontinuity 2: dip direction/ dip

1 2 Bedding attitude: horizontal; dipping into the slope (anaclinal); obliquely relative to the slope; obliquely (orthoclinal); obliquely (plagioclinal); downslope (cataclinal); downslope stepper than slope; dipping out of the slope; parallel to slope

1 2 Rock mass structure: massive; stratified; fissile; moderately jointed; fractured; schistose; vacuolar; chaotic

1 2 Joint spacing: very wide (> 2m); wide (60cm - 2m); moderate (20cm - 60cm); close (6cm - 20cm); very close (<6cm)

1 2 *Geotechnical properties: rock; lapideous rock; weak rock; debris; grained soil; dense grained soil; loose grained soil; cohesive soil; firm cohesive soil; soft cohesive soil; organic soil; complex unit; alternating beds; mélange

1 2 Weathering: fresh; slightly weathered; moderately weathered; higtly weathered; completely weathered

Notes

1 2 *Lithology: limestone; travertine; marl; limestones-marl flysch; sandstone, arenaceous flysch; shale, pelitic flysch; acid extrusive rock; basic extrusive rock; pyroclastic rock; acid intrusive rock; basic intrusive rock; metamorphic rock weakly foliated; metamorphic rock foliated; evaporite; sedimentary siliceous rock; conglomerate or breccia; debris; gravel; sand; silt; clay; mixed soil; made ground

***LAND COVER**

urban areas; mineral extraction sites; arable land; Annual crops associated with permanent crops; permanent crops; riparian vegetation; reforestation; coppice woodland; forest trees; sparsely vegetated areas; bush; pastures

***SLOPE ASPECT**

N; NE; E; SE; S; SW; W; NW

HYDROGEOLOGY

Superficial water: absent; stagnant; diffuse runoff; concentrate runoff
Springs: absent; diffuse; local
Groundwater: absent; unconfined; confined
N° | Depth (m)
Notes

CLASSIFICATION

*1°liv | 1 2 *Type of movement (unclassified): fall; topple; rotational slide; translational slide; lateral spread; slow earth flow; rapid debris flow; sinkhole; complex landslide; deep-seated gravitational slope deformation; area affected by rockfalls/topples; area affected by sinkholes; area affected by shallow lanslides

1 2 Rate of movement: extremely slow (< $5*10^{-10}$ m/s); very slow (< $5*10^{-8}$ m/s); slow (< $5*10^{-6}$ m/s); moderate (< $5*10^{-4}$ m/s); rapid (< $5*10^{-2}$ m/s); very rapid (< 5 m/s); extremely rapid (> 5 m/s)

1 2 Material: rock; debris; earth

1 2 Water content: dry; moist; wet; very wet

Notes:

ACTIVITY

*State (unclassified): active; reactivated; suspended; dormant; stabilized; artificially stabilized; abandoned; relict
Distribution: moving; retrogressive; widening; enlarging; advancing; diminishing; confined
Style: single; complex; composite; multiple; successive

Figure 1: Excerpt of the IFFI Landslide data sheet.

As of early 2007, the Italian Landslide Inventory holds about 470,000 landslides and represents the first homogeneous and updated archive with a detailed spatial representation of landslides (Trigila and Iadanza, 2007). The IFFI Inventory has been used by Italian River Basin Authorities for landslide risk mitigation actions.

To provide Internet access to the geospatial information of the IFFI Project, APAT has designed the WebGIS application Cart@net-IFFI (Fig. 2) and the Web Map Services (WMS). The IFFI website (www.sinanet.apat.it/progettoiffi) is focused on promoting and spreading out the landslide information to national and local institutions, research institutes, geologists, engineers and citizens.

Through a simple and clear navigation, the user can view the landslides of the IFFI Inventory together with other vector layers (urban areas - Corine Land Cover 2000, roads and railways, administrative boundaries and drainage network) and raster layers (the digital terrain model, digital orthophoto TerraItaly it2000, Landsat satellite images and IGM topographic map). Moreover, it is possible to obtain information on the most important landslide parameters, and view documents, photos and videos. The IFFI website runs since 2005 and over 200,000 hits have been counted to date.

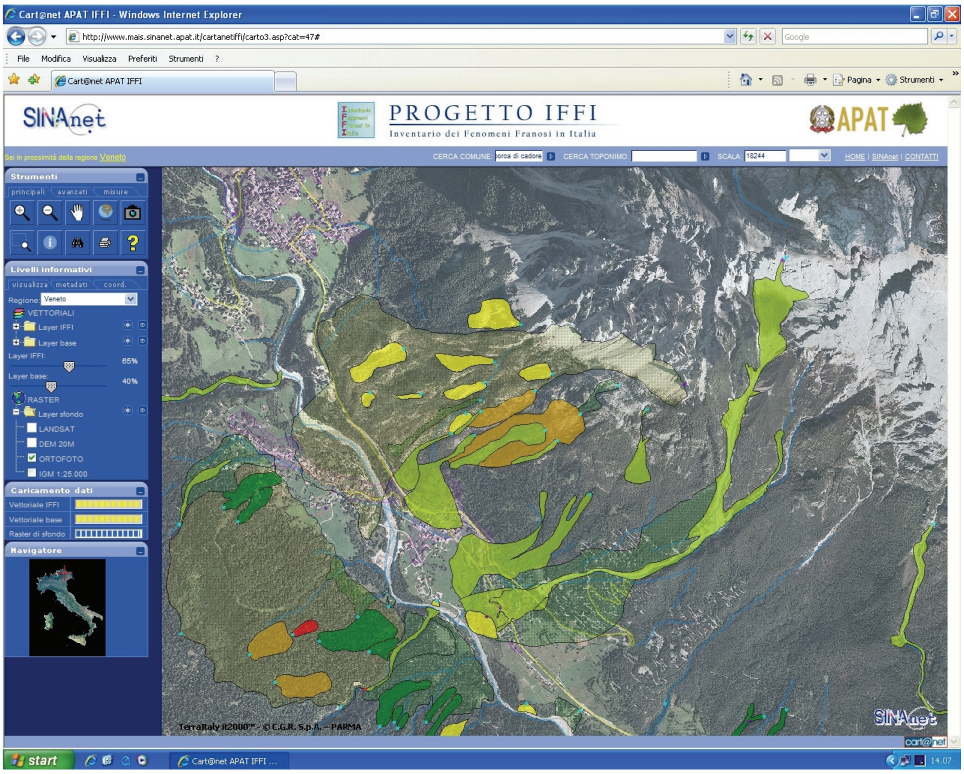

Figure 2: IFFI Project WebGIS interface.

The WMS services of the IFFI Inventory have also been developed in accordance with the European Directive INSPIRE 2007/2/CE (Infrastructure for spatial information in Europe) and the Open GIS Consortium specifications (OGC, 2006). This interoperable service allows the users to build a customized map overlaying the IFFI landslides theme with additional layers stored on their PC or provided by different Internet map servers. The user can access the WMS service through a WMS viewer, as the one provided by the INSPIRE Geo-portal (Fig. 3), or through GIS software.

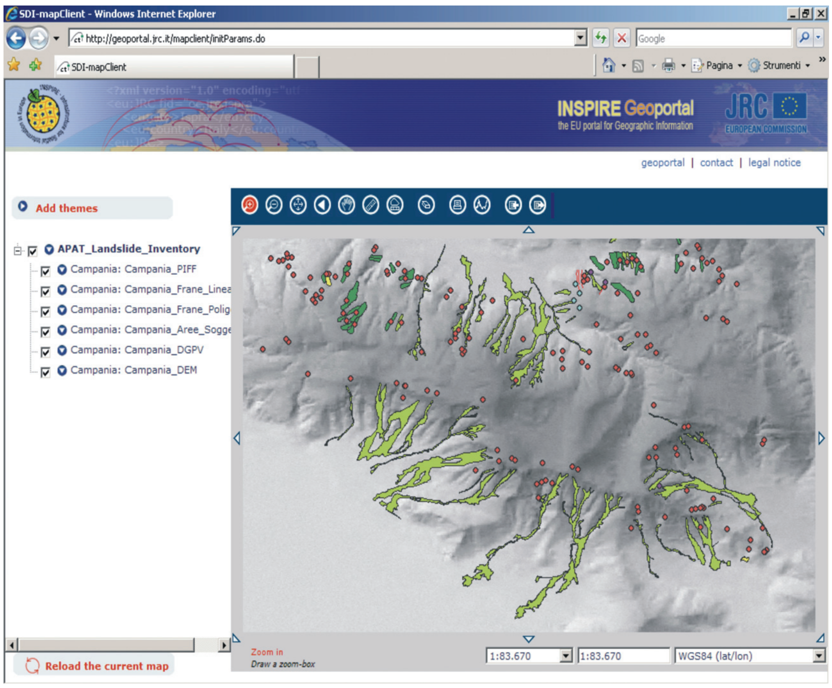

Figure 3: Extremely rapid debris-mud flows in Sarno (Campania), 1998. IFFI WMS services as displayed on the INSPIRE Geoportal.

In 2007, APAT published the Italian Landslide Report (APAT, 2007). The report describes methodology, guidelines and includes statistics and regional landslide reports.

Next steps: APAT is going to design a WebGIS application for remote updating of the IFFI geo-databases via Internet.

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IGME landslide database and a review of hazard zonation in Greece

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Landslides are a common phenomenon in Greece mainly in the western and central part, where the morphological relief is characterised by the presence of high mountains with steep slopes, as a result of recent tectonic activity in conjunction to weathering processes (Poyiadji et al., 2005). The aforementioned areas consist of relatively recent geological formations of alpine and post alpine age, which are highly fractured due to intense deformation and usually covered by a thick weathering zone.

Last years there was an increase in the density and diversity of landslides all over Greece, even in the eastern part, triggered by heavy rainfalls. Moreover, in the summer of 2007 extensive wildfires which resulted in the deforestation of a large area in Peloponnesus are expected to affect more dramatically the activation of landslides.

Landslides that affect either urban areas or major transport network cause major social and economical impacts without ignoring life losses as well. A great number of landslides are due to the reactivation of older ones, while many of them are triggered by human activity.

One of the main activities of IGME is to follow up with landslides and give first aid solutions, especially to small and remote villages. Doing that for over seventy years resulted in the creation of huge amount of information. There are about 2600 reports in analogue form concerning landslides in Greece. Considering that many of them describe the engineering geological situation in more than one settlement and that in every settlement are more than one landslide then the recorded number of landslides is much greater.

The creation of a digital database of landslides was a necessity for IGME. Such database was created few years ago and contains 250 cases of landslides that were studied during 2.5 years. The database was created using ACCESS and includes fields like:

- <u>Geographic details</u>
  Prefecture, municipality, year, season, coordinates.
- <u>Location</u>
  Elevation, land use, slope gradient, erosion, geotectonic zone, geological formation, lithological composition, permeability, inclination of strata, thickness of weathered zone, precipitation, manmade impact, groundwater level, seismic risk zone.
- <u>Landslide data</u>
  History, type of movement, geometry, rate.
- <u>Landslide process</u>
  Triggering factor, causes, consequences, structures affected, proposed mitigation measures, degree of effectuality of mitigation measures.

IGME is in the process of creation of an Integrated Geo-data System, which will include, among others, the landslide database. The design of the system is almost completed and during 2008 the landslide reports (2600) will be digitised and included in the database.

The first attempt to present the landslides problem on a nationwide scale was the map of landsliding urban areas, which was part of the Engineering Geological map of Greece at 1:500,000 scale, published in 1993 (Fig. 1).

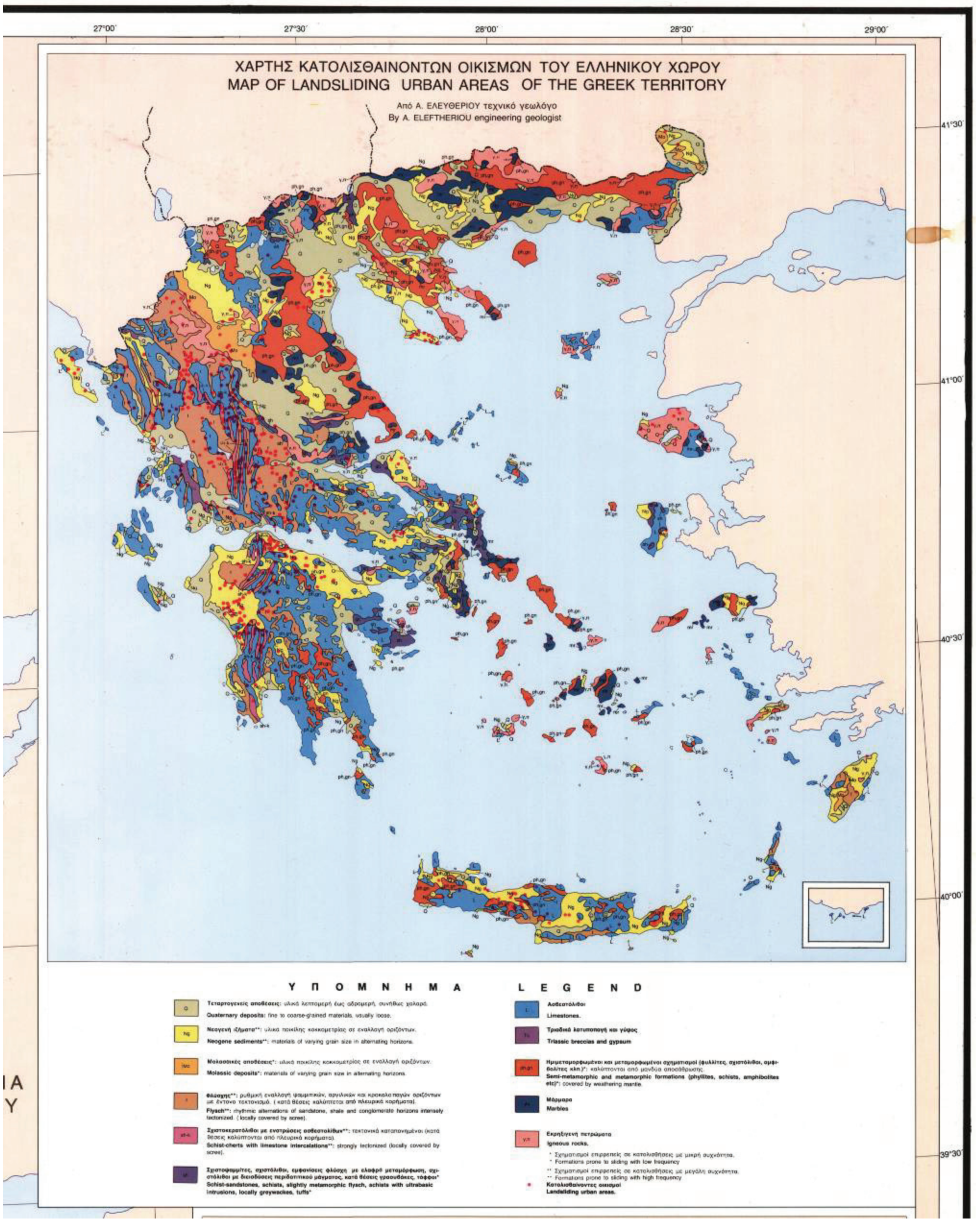

Figure 1: Map of landsliding urban areas, represented as red dots (Part of the Engineering Geological Map of Greece, scale 1:500,000, 1993).

A landslide hazard zonation map of Greece was recently produced at a scale of 1:500,000 according to the number of landslides per 100 Km^2 (Koukis et al., 2005) (Fig. 2).

Engineering geological and geotechnical maps are also produced at larger scales depending on their purpose, varying from 1:50,000 for the level of counties to 1:1000 for planning development of urban areas (Arvanitidis et al., 2005) (Fig. 3).

The compilation of these maps with specific criteria for a multi-hazard approach is leading to the zonation of the urban areas in respect to their susceptibility to hazards (Fig. 4). For each zone of “geological suitability” instructions are given for safe development of structures if the zones are “suitable” or if the risk is high then the area is totally excluded from building development.

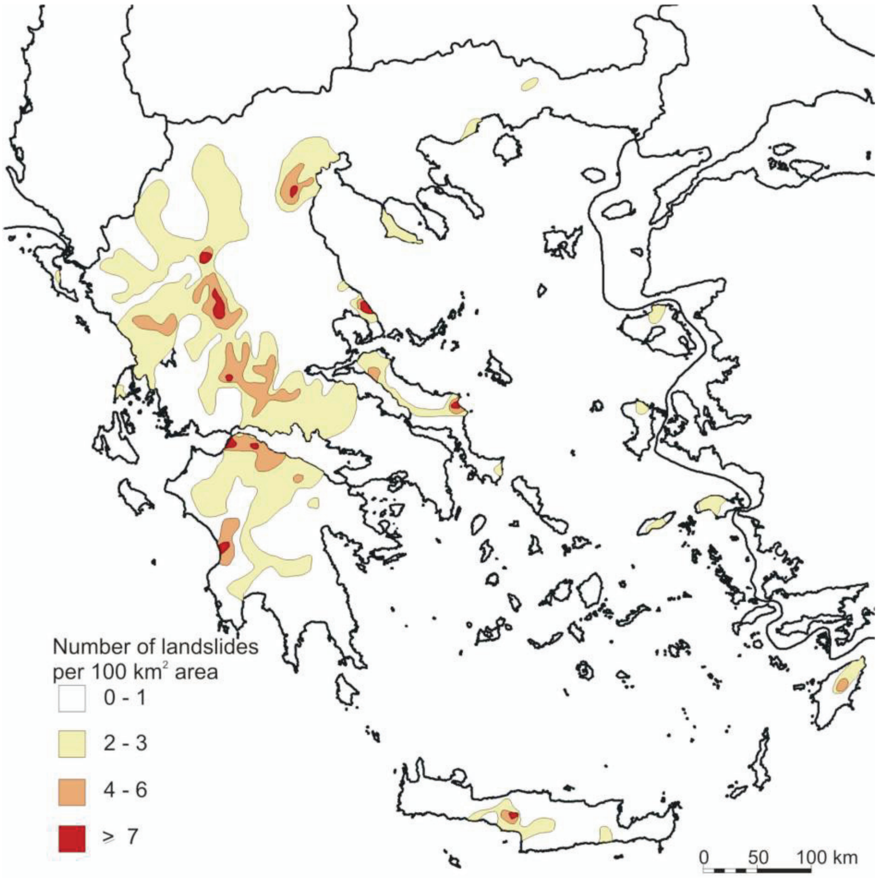

Figure 2: Landslide hazard zonation map of Greece at 1:500,000 scale (Koukis et al., 2005).

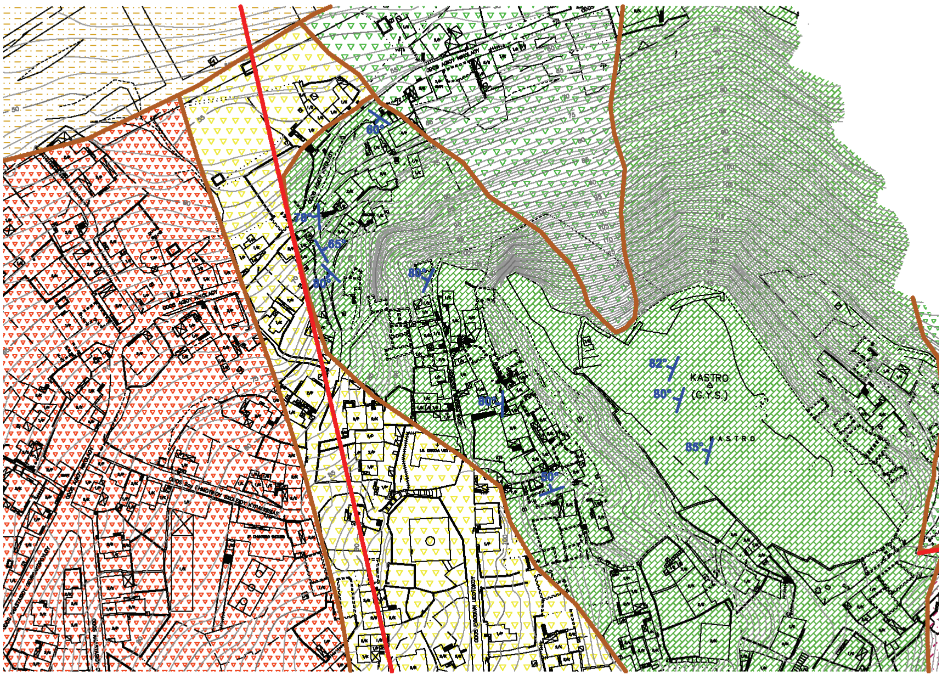

Figure 3: Geotechnical map of an urban area in Kyparissia town, Southwest Greece (original scale 1:1000). Green triangles represent loose scree; yellow triangles, loose to semicohesive scree of small thickness; red triangles, semicohesive to cohesive talus cone of great thickness; brown dashes and dots, semicohesive to cohesive marls, and green pattern, limestones.

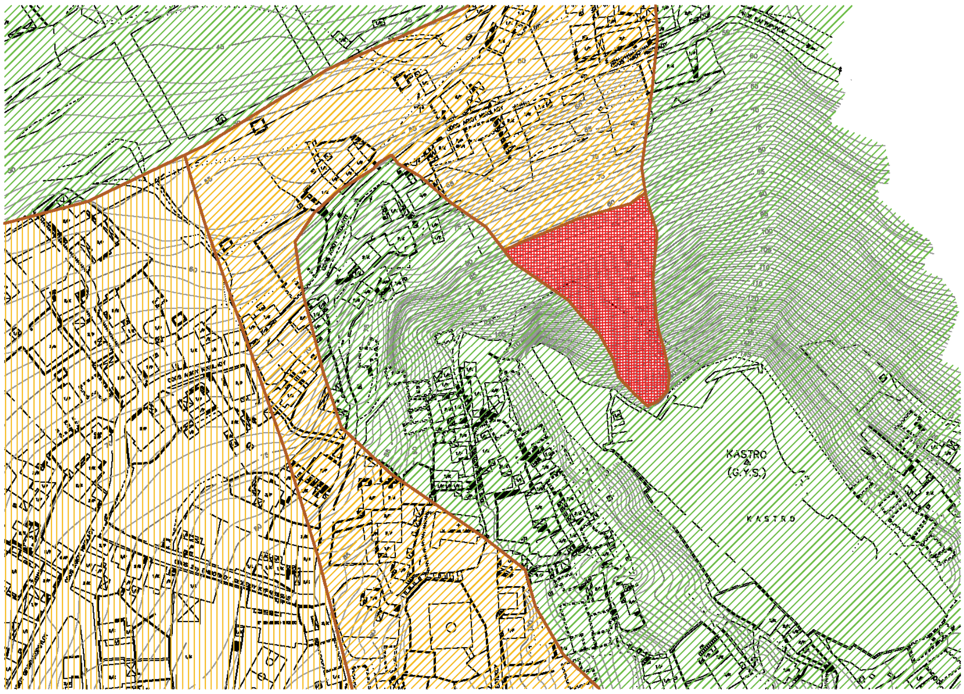

Figure 4: Geological Suitability Map of the same area as in Fig. 3 (original scale 1:1000). Red zone is covered by loose scree and in combination with the steep slope makes the area unsuitable for building (high seismic and landslide risk). Green zones are outcrops of limestone and marls where building is permitted. Orange zones are areas where building is permitted under certain conditions.

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Landslide susceptibility, hazard and risk GIS mapping in the Betic Cordillera (Spain): areas with limited information about triggering factors

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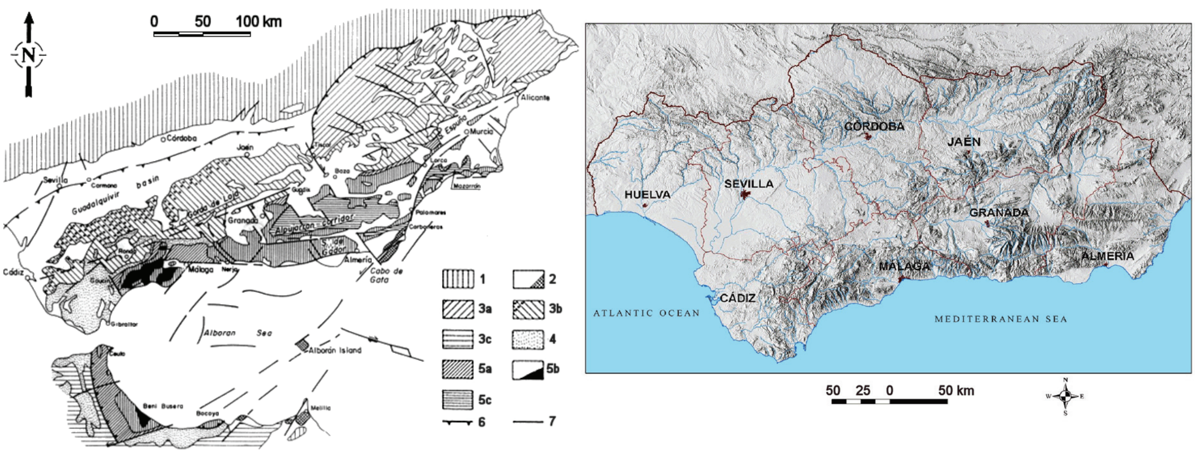
The Betic Cordillera is an Alpine belt, developed by orogenic processes in Upper Mesozoic to Tertiary times and uplifting during Late Miocene to Quaternary times, during the collision between the Eurasian and African plates. Limited to the North by the Hercynian belt and to the South by the Mediterranean Sea, it includes fluvial valleys, middle mountains and also the highest Iberian mountains (Sierra Nevada, 3492 m). The Betic Cordillera extends from the Eastern Balearic Islands to the SW corner of the Iberian Peninsula and covers most of the Andalusia region, a territory of 87,599 km^2 and 7,314,644 inhabitants (Fig. 1).



(A) (B)

Figure 1: A) Geological domains in the Western Mediterranean (Sanz de Galdeano, 1994) 1. Homeland; 2. Neogene basins; 3. External Zones; a: Prebetic, b: Subbetic, c: Rif. 4. Flysch units. 5. Internal Zones; a: Maláguide and dorsal, b: Alpujárride and Peridotite, c: Nevado-Filábride. B) Illumination model of Andalusia showing orographical features and its eight provinces.

Climate conditions in Andalusia correspond to six different Mediterranean zones: Atlantic coastal oceanic, Subtropical, Sub desert, Semi-continental with hot summer, Continental with cold winters and Mountain climate. Average monthly temperatures range from the coldest January in Granada (6.4 ºC) to the hottest August in Écija (Seville, 28.5 ºC). In Central and Eastern Andalusia, the snow covers Sierra Nevada Mountains and surrounding chains from November to May, until subtropical cultivations widespread along coastal areas, only 30 km away from the sky station in Sierra Nevada. Rainfall is unevenly distributed along 40% of the year, with local variations. The meteorological records, available since 1961, show seven relative drought periods: 1960-61, 1964-69, 1970-71, 1973-77, 1980-86, 1988-96 and 1998-99, with rainy periods in 1969-70, 1971-73, 1977-80, 1986-1988, 1996-97 and currently since September 2007. These rainfall events affected irregularly the four main river catchments: Guadalquivir River (most of Andalusia), Guadiana River (Western border), Segura (Eastern border) and Southern coastal slopes along Cádiz, Málaga, Granada and Almería provinces, with very variable local intensities.

The geology of the Betic Cordillera is divided into three regional tectonic units: the External Zones, composed by Triassic to Tertiary limestone and marl units, to the North; the Internal Zones composed by metamorphic rocks in two main units, Nevado-Filábride and Alpujárride, cropping out along Sierra Nevada, and Southern coastal slopes composed by quartzite, schist, phyllite, marble and minor gneissic and peridotite bodies; and finally some postorogenic basins in filled by Upper Tertiary to Quaternary sediments evolving from marine to fluvial deposits during the uplifting of the South Iberian crust. There is a moderate seismic activity which concentrates the highest expected earthquake hazard around the provinces of Granada, Málaga and Jaén. Nevertheless, the currently obligatory anti-seismic technical regulation of civil works and building projects pays little attention to terrain dynamic behaviour. Geomorphic indexes of active tectonics showing significant correlations with the observed landslides distribution, indicate recent increasing slope instability associated to active faults, river over-excavation and seismic activity (El Hamdouni et al., 2007) under controlling geotechnical properties (Fernández et al., 2007). An intense erosive denudation affects the region due to a variety of convergent processes of environmental, social and economical origin. Thus, historical sudden withdrawal of agricultural and forest maintenance practices, progressive changes in land use with intensive country to city migration and the corresponding urban growth, and new urbanization around cities and along the coast, give place to increasing new risk areas threatened by flash flooding and landslides, with catastrophic consequences in terms of damages and life losses.

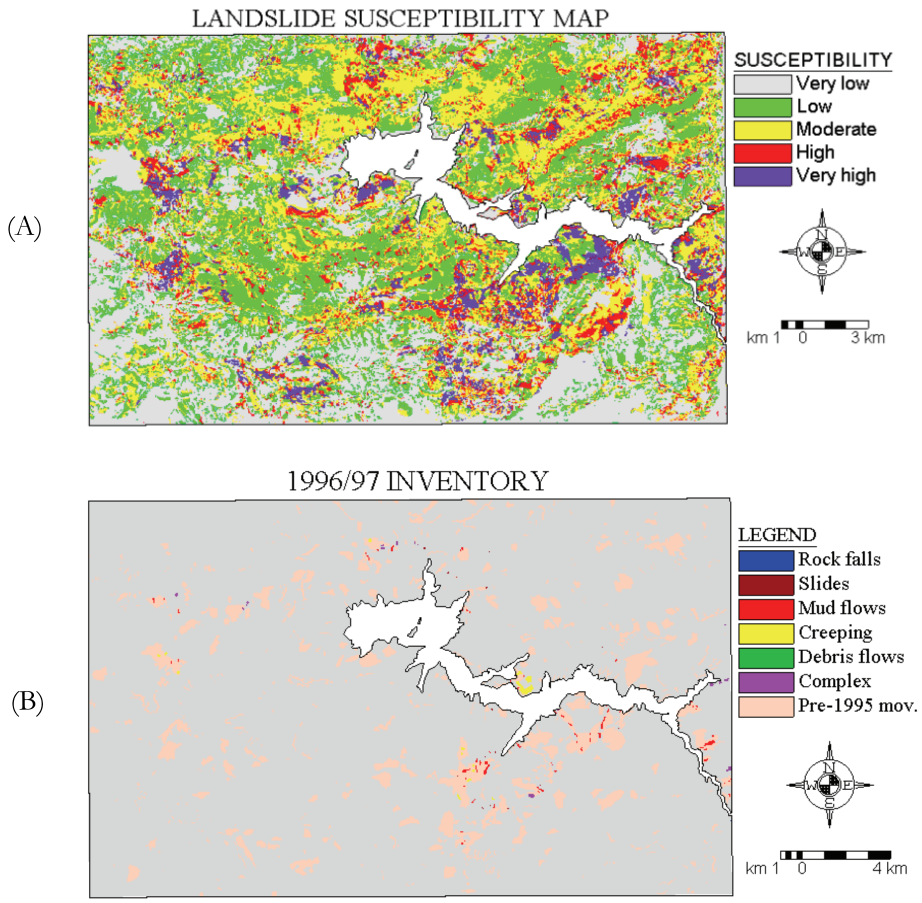
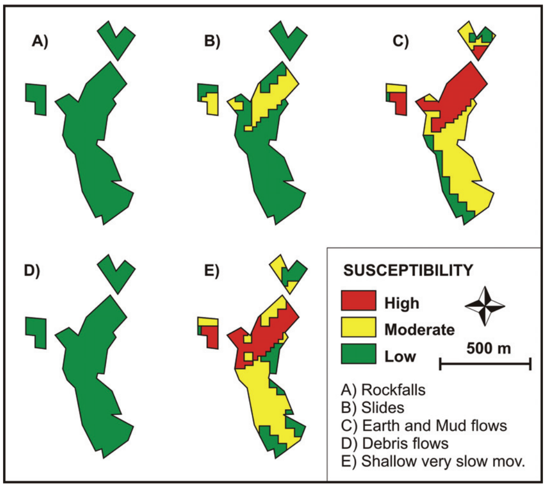


Figure 2: A) Landslide susceptibility map made in 1993-1995 in the Iznájar dam area (Granada, Spain) representing the assessment of an integrated landslide inventory comprising all types using the GIS matrix method and B) Inventory of landslides triggered by rainfall in 1996-1997. These data were used for a validation assessment of the GIS matrix method (Irigaray et al., 2007).

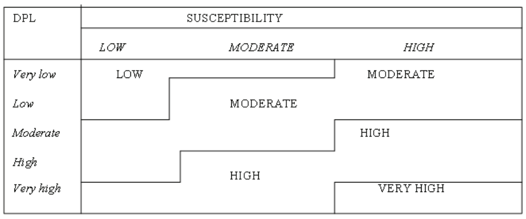
(A)



(B)

m³ SIZE	*Shallow very slow slope mov.*	*Earth & Mud flow*	*Debris flow*	*Rock fall*	*Slide*
1 *SMALL*	VERY LOW	LOW	MODERATE	MODERATE	MODERATE
50				HIGH	HIGH
MIDDLE	MODERATE	HIGH	HIGH		
500 *LARGE*	LOW	HIGH		VERY HIGH	
5000 *VERY LARGE*					VERY HIGH
50000			VERY HIGH		
EXT. LARGE	MODERATE	HIGH			

(C)



(D)

Figure 3: Example of recommendations for further assessment of landslide risk in a small village (Granada, Spain). A) View of the village. B) Landslide susceptibility maps obtained from the Provincial Landslide Susceptibility Map. C) Qualitative classes of Destructive Potential of different types of landslides (DPL) depending on landslide size. D) Summary recommendations: Shallow very slow slope movements: low. Earth and mud flows: low, moderate or high hazards in the low, middle and high susceptibility zones. Risk may also attain high level depending on size and speed of the mass. Slides: depending of the destructive potential of the expected slide, the resulting hazard may be between moderate to high (Chacón et al., 2006b).

From several thousands of landslides inventoried in the last thirty years, the following general features may be pointed out: small-sized, shallow landslides of earth flow type with slide and rockfall on marls and limestone predominate in the External Zones and Postorogenic basins. Debris flows, slides and rockfalls are observed in the Internal Zones, with some medium-sized deep-seated slides associated to river channel over-excavation or large earthquakes. Deep-seated slides are, in general, in "dormant stage" or very low activity, as shown recently by DInSAR assessment (Fernández et al., 2006). Landslide susceptibility mapping by the GIS matrix method has been developed and validated (Fig. 2) to obtain maps at different scales and a Model Builder application in ArcGIS has been recently prepared to make easier the development of susceptibility maps. At scales from 1:200,000 (Granada) to 1:25,000 and 1:10,000 (for selected areas of Málaga, Granada, Jaén and Almería) different landslide susceptibility maps are the result of research projects, PhD Theses and documents for local land-use regulations (Fig. 3). At 1:5,000 scale a landslide susceptibility map was obtained based on a model of planar failure on infinite slopes, and supported by geotechnical soil and rock mechanical properties, water pressure and field conventional surveying (Chacón et al., 2006b; Irigaray et al., 2007; Jiménez et al., 2007). Also 1:200 GIS linear mapping was prepared, using the SMR index, in cuts along a road section on metamorphic marble in the Granada coast. Currently a GIS project for the Geotechnical Anti-seismic Map of Andalusia, covering the metropolitan area of the eight capitals of the region, for the Regional Administration of Public Works, is being finished at scales 1:400,000 to 1:50,000 with a layer showing available local geotechnical data.

Concerning hazard and risk mapping, a very short number of triggering events clearly related to inventoried landslides were distinguished in a wide variety of local climatic conditions. In the available meteorological record (1960-2007), only two known regional rainfall events triggered landslides in the Guadalquivir valley (1963 and 1996) and one along the coastal areas (1996). Concerning seismically triggered landslides, some few cases may be identified in relation with only two known large catastrophic earthquakes (1755 and 1884) and one more during a local earthquake (1956). In general, the recorded consequences of landslides triggered by rainfall amount to moderate damages although threatening repeatedly some sections of local or regional roads. This limited information on temporal data makes it difficult to establish significant "return periods" to propose a systematic hazard and risk mapping, although it could be possible in some few areas where enough local information on historical landslides is available. Alternatively, in present times geotechnical or physical models, with available data on critical basic accelerations for the expected maximum earthquake (return period of 500 years), are applied to the preparation of medium to large scale landslide hazard maps for dynamic conditions. The concept of landslide susceptibility may also be extended to obtain a qualitative landslide hazard map or risk map at medium to large scales. It is based on the assumption of landslide susceptibility as indicating likelihood of new landslides (Chacón et al., 2006a; Einstein, 1988). Some examples from areas of the Betic Cordillera are presented and their validity discussed.

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Landslide susceptibility and hazard mapping in high mountain regions: Application in the Italian Alps

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Introduction.

The situation of natural hazards in Italy has given in the last years a new strength to the research and application of effective prevention and mitigation measures by the Italian Government. Within this framework, this paper aims to illustrate some progress in landslide hazard and susceptibility assessment coupling two methodologies, characterized by different approaches: the first one is a semi-deterministic method that is focused on the evaluation of the hazard due to existing landslides; the second one is a bivariate statistical analysis to evaluate the landslide susceptibility at the basin scale. The combination of these two approaches was applied to a study area in the Dolomites, north-eastern Italy, within the National Programme on Geological and Geothematic Mapping, with interesting results concerning land use planning and risk management. Starting from detailed geological and geomorphological surveys and historical and bibliographical analysis almost 900 landslides where mapped and classified on the basis of their typology, recurrence and main morphometrical parameters. Moreover, seven thematic maps concerning triggering factors for different landslide typology were also carried out. These data have been analysed by means of GIS techniques in order to assess the hazard level related to each mapped phenomenon.

Methodology

The methodology here presented exploits the potentialities inherent to two methods. The first one is the so called Swiss Method, a three-step procedure of hazard identification, hazard assessment and risk management, useful to determine the hazard levels related to each investigated landslide. The second one is the Weights of Evidence Modelling Technique, a statistical bivariate approach, here applied as a powerful exploratory tool in order to define the landslide susceptibility in the areas nowadays not affected by landslides.

The Swiss Method

In the study site, the Swiss Confederation semi-deterministic approach developed by Heinemann et al. (1998) has been adopted. This method allows greater objectivity in the definition of the parameters that are used to determine hazard by means of calculation matrices that produce a high rating value on the basis of the combination of probability of occurrence, understood as frequency, and the magnitude of the phenomena.

The need to operate at a regional scale, as in this case study, has suggested the adoption of a simplified methodology to render results and risk elements homogeneous by defining, for each landslide, only the hazard. The determination of vulnerability and risk has been deliberately neglected since it could not be proposed at the scale utilised for this research.

The essential stages of the methodology adopted are:

- identification of landslide processes (Landslide Inventory Map);
- assessment of the intensity or magnitude of disarray processes;
- assessment of hazard;
- identification of existing or potentially vulnerable elements.

The basic and fundamental element for assessing landslide hazard and risk should be a map of landslides containing the following elements:

- type of landslides;
- affected or prone areas;
- state of activity;
- characteristic geometric parameters;
- possible evolution of the phenomenon.

Since intensity or magnitude are difficult to quantify correctly we decided to calculate them only in terms of velocity (Fig. 1) and volume (thickness or diameter of blocks in case of rockfalls) of the rock mass that can be set in motion (geometrical severity, Fig. 2). Furthermore, a differentiation of velocity classes has been carried out by distinguishing between infrastructures, estate assets, economic activities and people. This implies the implementation of two separate hazard maps concerning infrastructures and human beings respectively.

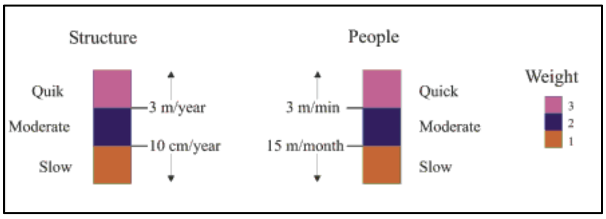

Figure 1: Velocity.

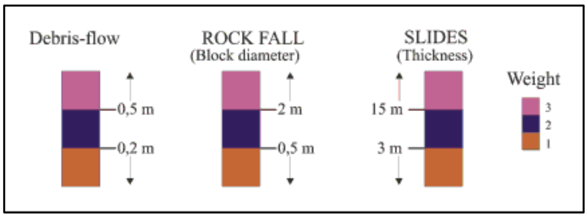

Figure 2: Geometric severity.

The combination of rating values relative to velocity and geometrical severity, deduced from Fig. 1 and 2 and calculated for each identified process, allows to calculate a new matrix whose values define the magnitude of the process.

Besides the spatial forecast (possibility of occurrence in a given area – Map of Landslides) and the forecast of the type and evolution of the event (magnitude), the hazard assessment requires also a temporal forecast (when a given event is likely to happen). This may present considerable difficulties due to lack of sufficient historical data for statistically determining frequency. For this reason four classes of landslides have been considered in this study:

- Active landslides (continuous);
- Non-active landslides;
- Dormant landslides with return time lower than 50 years;
- Dormant landslides with return time higher than 50 years.

The methodological scheme utilised allows to define a basis matrix, according to which, one of the four hazard classes listed in Fig. 3 will be assigned to each landslide process examined.

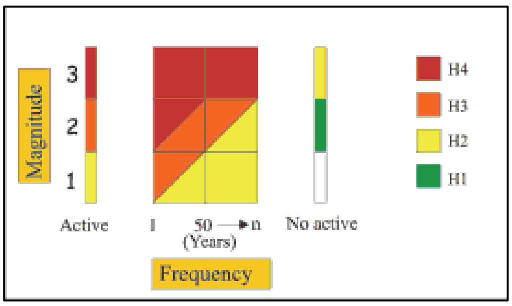

Figure 3: Hazard linked to the magnitude.

The four hazard classes obtained might now have a sort of correspondence with the four risk classes identified by Law no. 267/98, since the possibility of damage to assets and people can be associated to each of the hazard classes, although the difference has to be clear.

Weights of Evidence Modelling Technique

Weights of Evidence (Agterberg et al., 1989) is a quantitative method for integrating multiple sources of evidences to solve the problem of predicting the occurrence of an event where known evidences are available. The aim is to produce a favourability map useful to predict the future distribution of landslides (events) in the study area. All data useful for the analysis have been derived from fieldwork, photo interpretation and existing databases. The landslide inventory map and the predictor patterns supporting information on landslide conditioning factors have been collected, critically reviewed, digitised and entered into the project database, managed within a GIS. The following maps have been initially considered: landslide inventory map; morpho-structural map representing detailed morpho-structural elements; distance from tectonic lines, distinguished by typology, buffering the main tectonic discontinuities; land use map indicating the main land use units that might affect the hydrological condition and soil strength; distance from rivers, buffering the streams of different orders; slope geometry, such as altitude, slope angle, aspect, longitudinal and transverse slope curvature. Besides, additional parameters such as watershed area, drainage density, drainage network order, channel length, etc. have been derived.

For analysis purposes all thematic maps have been converted to raster format with 5 m pixel size.

Results

As output of this combined methodological approach three different maps were produced. The hazard map derived by the Swiss method shows the present hazard of the mapped landslides (Fig. 4); on the other hand, the result of the Weight of Evidence method for the evaluation of the susceptibility gave correct indications about the proneness to future landslide movements in the area mapped by the Swiss method as no hazard. On the basis of the calculated weight values, two posterior probability maps (representing favourability to landslide) have been computed (Fig. 5a, 5b), one for each type of landslide.

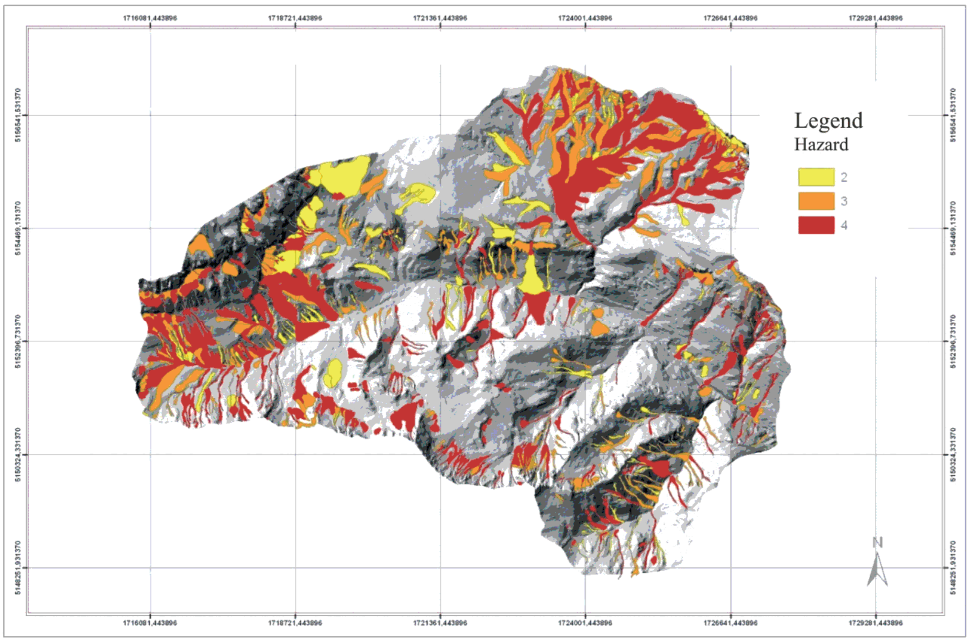

Figure 4: Hazard levels for the mapped landslides derived by the "Swiss method".

(a)

(b)

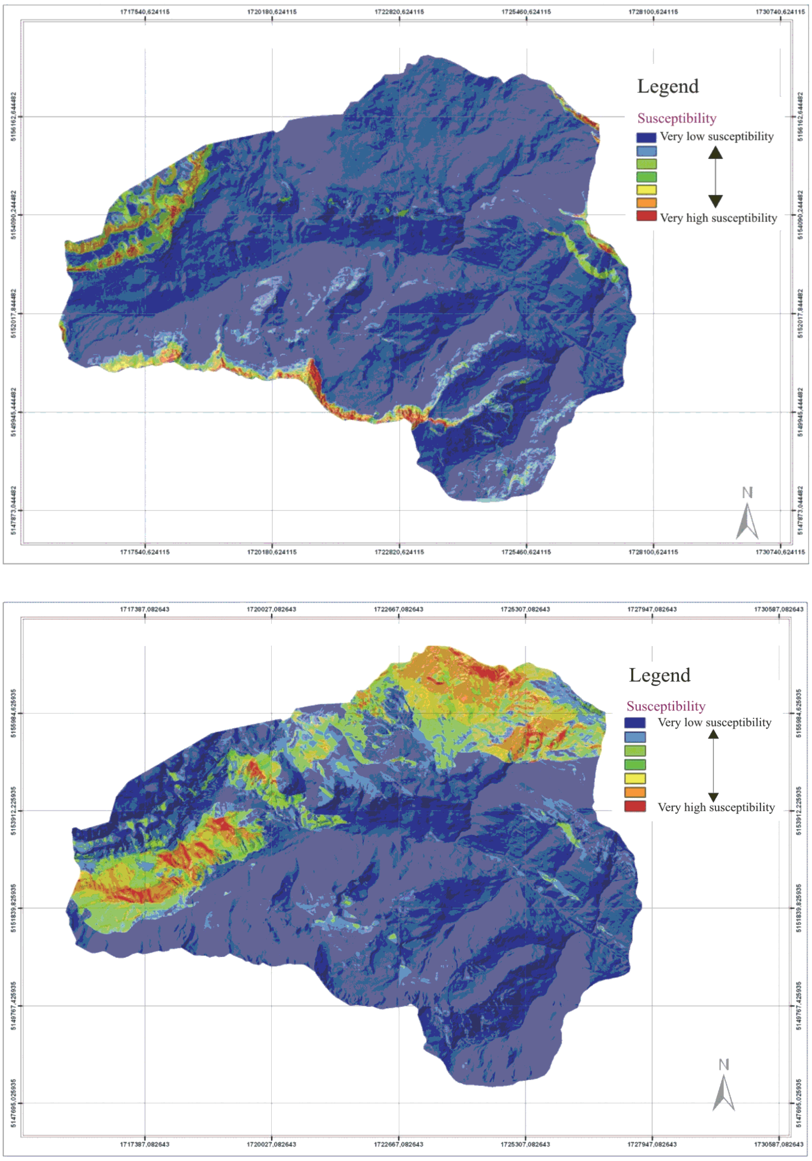

Figure 5: a) debris flow susceptibility map of the upper Cordevole Basin; b) earth flow susceptibility map of the upper Cordevole Basin.

The reliability of the final maps has been confirmed after considering a new group of landslides, initially not available in the landslide dataset. According to the Swiss method, they have been distinguished on the basis of the hazard, and more than 90% of these new events are located within areas characterized by high degree of susceptibility. This test can not be considered as a complete predictive test, but it may give some information about the quality of the results, strengthening the exploratory power of the model.

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Landslide risk zoning - what can be expected from model simulations? A tentative application in the South French Alps

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Landslides are both a challenge to develop and maintain a sustainable infrastructure in the European mountains, and a source of interest to government authorities and resource managers responsible for mitigating any risks they may impose. For an integrated management of the mountain territories, risk zoning schemes have to be developed in close cooperation with the government authorities in charge of the decision and the implementation of the risk plans (Fell et al., 2005).

This contribution focuses on the quantitative assessment of landslide risks and the production of risk maps through the use of GIS-driven models and technologies. It presents the methodology used in the small and specific territory of the Barcelonnette Basin (South French Alps) at a 1:10,000 scale. This methodology has been developed within the EC-funded project Alarm (Assessment of Landslide Risk and Mitigation in Mountain Areas, 2001-2004) and is in line with the French natural risk assessment methodology "*Plan de Prévention des Risques*".

The hazard and the potential consequences over this territory are specific. Regarding the hazard, the territory is affected by active landslides (large mudslides, shallow rotational or translational slides, torrent debris flows) and relict landslides (deep-seated rotational slides). The data available and the understanding of the mechanisms of these landslides (activity, movement rate, triggering and development mechanisms) are diverse. Regarding the assets, the territory is composed of several elements at risk and thus human, structural and functional vulnerability are distinguished.

The proposed methodology (Fig. 1) combines expert analyses, statistical analyses and model simulations (Malet et al., 2006). Our quantitative assessment is based on a five-step embedded procedure, and distinguishes the assessment of the hazard on the hill slopes and on the torrential fans:

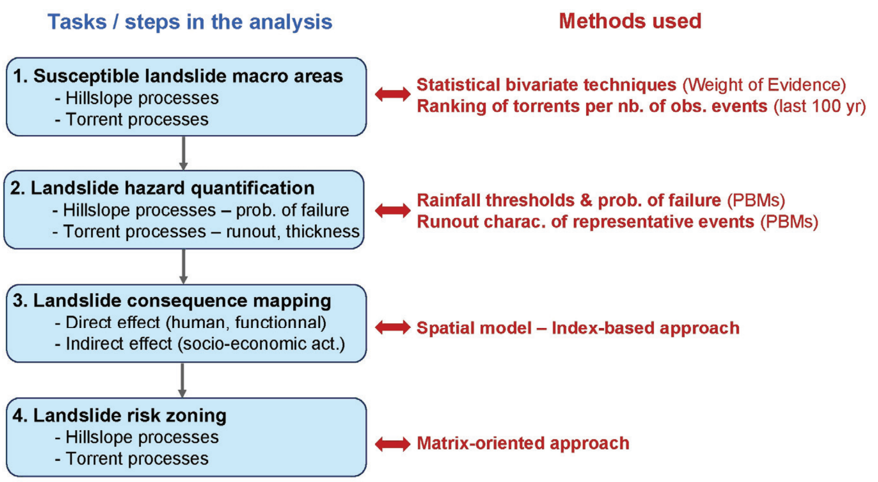

Figure 1: Flowchart of the model-based methodology developed for quantitative risk assessment and mapping.

(1) the use of a bivariate probabilistic model (weights of evidence) to locate the main susceptible source areas on the hill slopes, and derive spatial probabilities (Thiery et al., 2007). The model simulates the relationship between factors controlling landslide location and the past and present landslide distribution. Extent of the landslides is derived by combining statistical analyses of observed events and GIS calculations. Their triggering probabilities are simulated with a coupled hydrology-slope stability model, and critical rainfall thresholds are identified through Monte-Carlo simulations, and related to observed climatic time series (Malet et al., 2007). A hill slope hazard map is proposed with this procedure (Fig. 2).

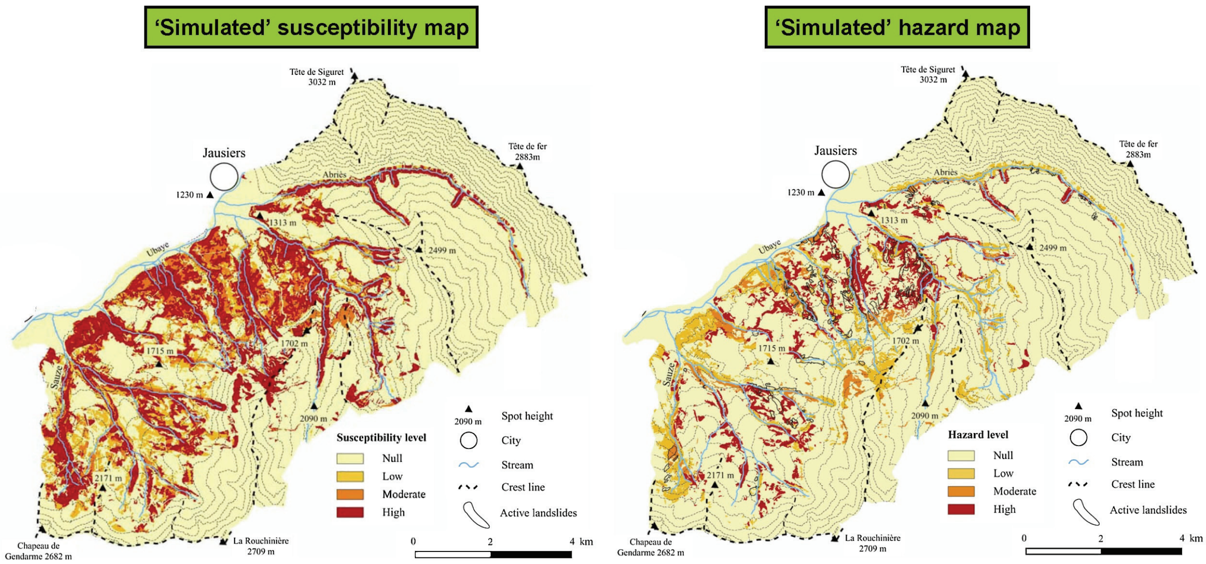

Figure 2: Susceptibility and hazard maps produced for the hill slope processes observed on the South-facing slope of the Barcelonnette Basin with the model-based methodology.

(2) the use of a process-based model of mass flow to estimate the extension of debris flows on the inhabited alluvial fans of the territory (Malet et al., 2005). The model computes the characteristics (runout distance, velocity, thickness) of low-frequency debris flows. The approach is based on Monte-Carlo techniques, combining a deterministic 2D flow model and a probabilistic description of the model input parameters (discharge, rheology of the debris). An alluvial fan hazard map is proposed with this procedure (Fig. 3).

(3) the integration of both hazard maps (hill slope hazard map, alluvial fan hazard map) in a global hazard map. This hazard map is spatially compared to a direct qualitative expert hazard analysis conducted along the standard of the French Ministry of Territorial Planning and Environment.

(4) the identification of the elements at risk and the evaluation of their vulnerability in terms of potential damage through the use of an index-based approach (Puissant et al., 2006) (Fig.4). The index uses some basic social, economical and environmental criteria to analyze on a hierarchical basis the direct assess (i.e. structural, functional and human damage potentials) as well as the indirect assets. This procedure is very general in scope and can be applied independently of the type of landslide hazard.

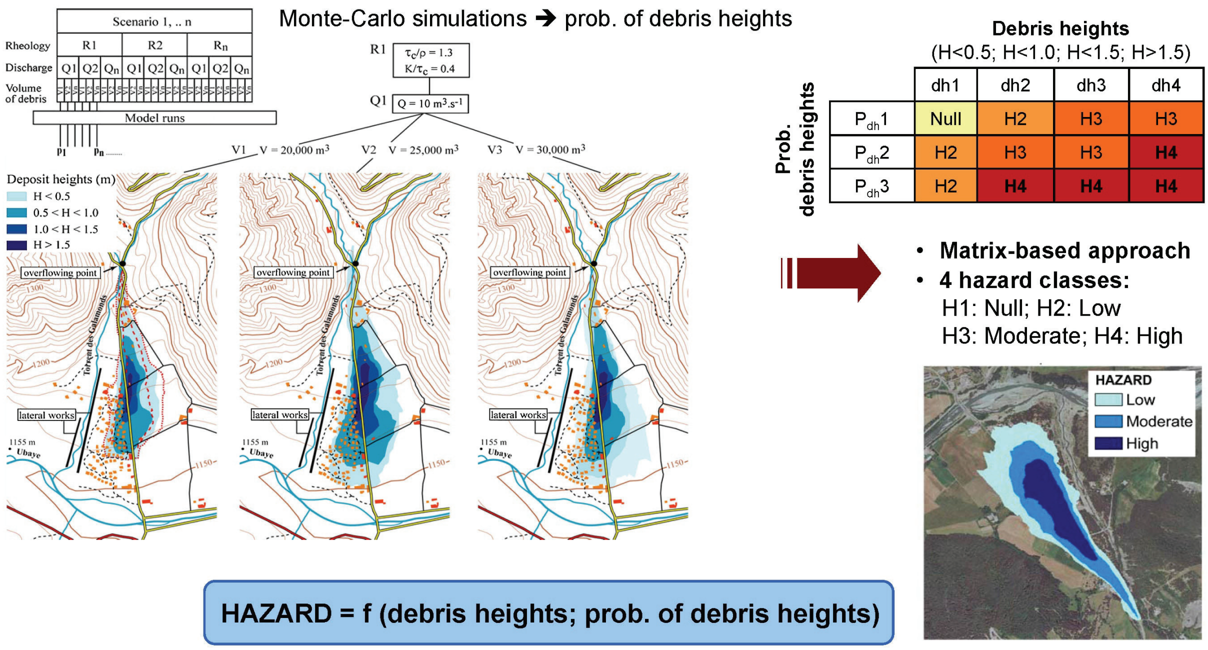

Figure 3: Hazard maps produced for the torrent processes observed on the torrential fans of the Barcelonnette Basin. Example of the Sauze torrent. The assessment is based on several debris flow runout simulations with a random sampling of input parameters derived from Probability Density Functions of torrent discharge data, debris volume and estimated rheological characteristics. Some criteria are applied to estimate hazard classes from the computed probabilities of runout.

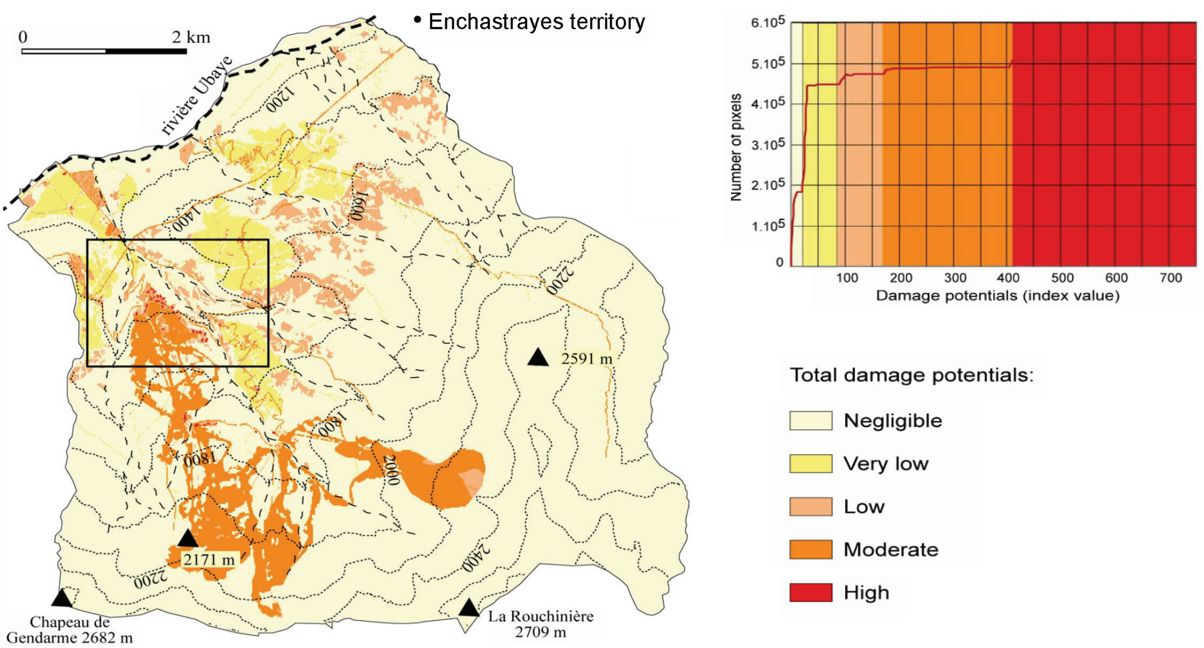

Figure 4: Map of potential consequences to landslides, computed with an index-based approach. Example of the territory of Enchastrayes, Barcelonnette Basin.

(5) the assessment and zoning of landslide risk by combining the hazard maps and consequence maps obtained at the previous steps through a classical matrix-oriented approach. The final risk map comprises three levels (Fig. 5).

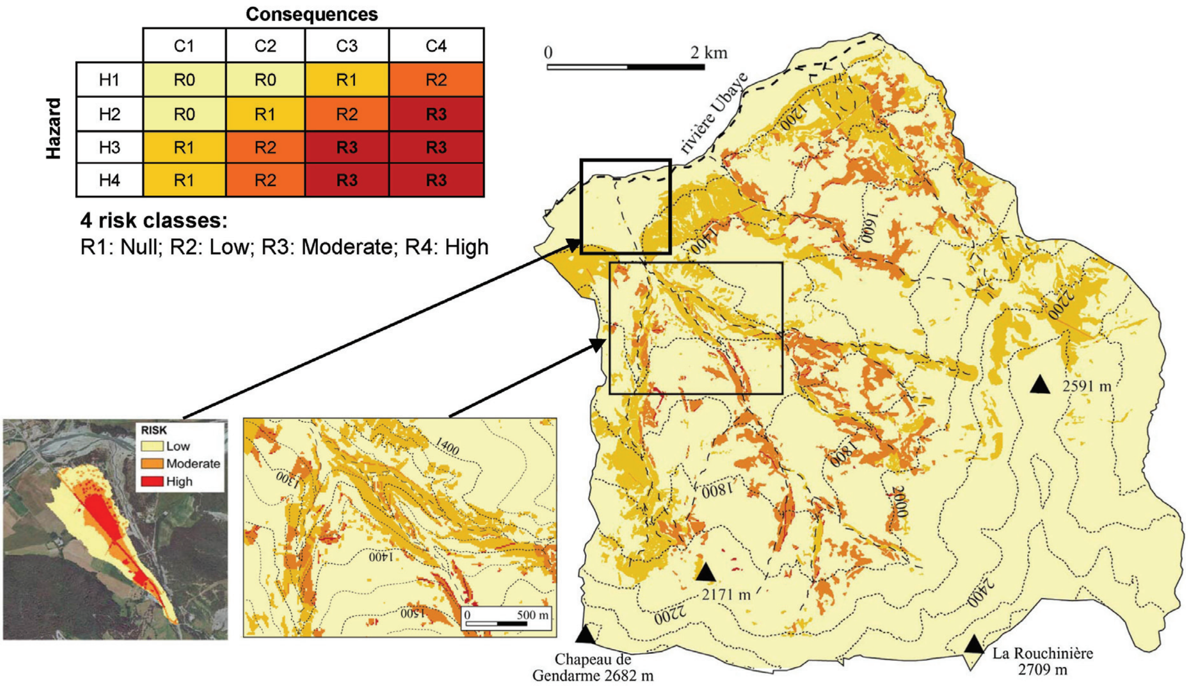

Figure 5: Landslide risk map computed by combining a hazard map and a map of potential consequence with a matrix-based approach (top of the figure). Example of the territory of Enchastrayes, Barcelonnette Basin.

Performance of the models and uncertainties in the model simulations are critically reviewed at each step of the methodology. If any doubt exists, the translation of the simulation results in the hazard and consequence maps goes in the direction of increasing the extension of the most hazardous and vulnerable zones.

Our contribution details the methodology used and presents the obtained hazard, consequence and risk maps. It stresses also the potentials (e.g. reproducibility) and limits (e.g. hypotheses on the landslide mechanisms and triggering thresholds) of combining spatial probabilistic models and process-based models for risk zoning if few data are available. Quantifying the uncertainties and the reliability of the model simulations are of paramount importance in the methodology.

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Criteria for the identification of landslide risk areas in Europe: the Tier 1 approach

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Landslides are local phenomena with potential regional and national consequences. In Europe, landslides pose a largely underestimated societal and economic threat. In the framework of the European soil thematic strategy, and the associated preparation of a directive on the protection and sustainable use of soil, landslides were recognized as a threat requiring specific strategies for risk assessment and management. The Soil Information Working Group (SIWG) of the European Soil Bureau Network (ESBN) developed a set of "common criteria" to identify areas where "soils are at risk" according to individual threats, including organic matter decline, erosion, compaction, salinisation and landslides. The proposed criteria adopt a nested geographical approach based on "Tiers" and exploit thematic and environmental data of different type, quality, and resolution using a variety of methodological and technological approaches. The Tier 1 assessment is aimed at the general (i.e., synoptic) identification of areas potentially subject to landslide risk, providing a low-resolution (1:1,000,000 scale) evaluation of landslide threats using existing thematic and environmental data. The Tier 2 assessment is intended to perform detailed analyses in the areas identified as potentially at risk by the Tier 1 assessment, and should provide results at a higher spatial resolution using existing and new data currently not available.

The main requirement for a Tier 1 assessment for the delineation of areas subject to soil threats in Europe is the availability of relevant input data (Eckelmann et al., 2006). At present, a continent-wide assessment of landslide susceptibility in Europe is feasible only adopting a qualitative evaluation technique. This is largely because systematic landslide inventory maps (i.e., maps showing the location and type of known landslides in an area) are not available for most European countries. The Tier 1 landslide susceptibility assessment can be performed using a reduced set of data, including information on the instability conditioning factors. Adoption of an index-based evaluation method can allow the production of a continent-wide landslide susceptibility map for Europe. The map will show areas not susceptible to landslides (i.e., areas where Tier 2 assessments are not required), and areas where a landslide threat exists, and where Tier 2 assessments are required.

Heuristic landslide susceptibility analysis is the simplest way to delineate landslide-prone regions when thematic information on ground material properties and topographic attributes are available, but information on the distribution of past and present landslides (i.e., a landslide inventory) is lacking (Guzzetti et al., 1999; Guzzetti, 2006). Heuristic modelling for landslide susceptibility comprises a variety of index-based approaches that relay on the *a priori* knowledge on landslide instability, i.e., on the assumption that the factors leading to slope instability in an area are known. Reliability of the method depends on how well and how much geomorphological processes acting upon a terrain are known and understood to the investigator. Instability factors are classified, ranked, and weighted, according to their assumed or expected importance in causing landslides. Based on this information, subjective decision rules are established to identify unstable areas. Ideally, rules used to rank, weight and combine the instability factors should be based on detailed knowledge of the physical processes controlling slope instability.

In Germany, a national landslide inventory map and associated geographical landslide database is not available. However, high-resolution thematic data on topography, lithology, and soil, are available and were used to prepare a synoptic landslide susceptibility map (Fig. 1). For the purpose, a three-step, heuristic procedure was adopted. First, the information stored in the German Soil Database (BÜK 1000) was analyzed. The 72 bedrock/soil associations listed in the national database were classified heuristically by expert knowledge into six classes, based on their expected susceptibility to landslides. Each bedrock/soil association was classified based on the rock/soil type, the degree of weathering, the soil/regolith thickness, the presence of permeability contrasts and nature of soil/bedrock interfaces, and the presence of discontinuities. Next, a 50 m × 50 m digital elevation model (DGM 50) was used to obtain a map of terrain gradient. The slope map was reclassified into six classes, based on the expected propensity to landsliding of each class of topographic gradient. Finally, the landslide susceptibility map based on lithology and soil types, and the susceptibility map based on terrain gradient, were combined. Combination of the two maps was performed on individual pixels (50 m × 50 m in size), adopting a weighted average technique and assuming the same importance (i.e., equal weight) for the topographic and the lithological/soil information.

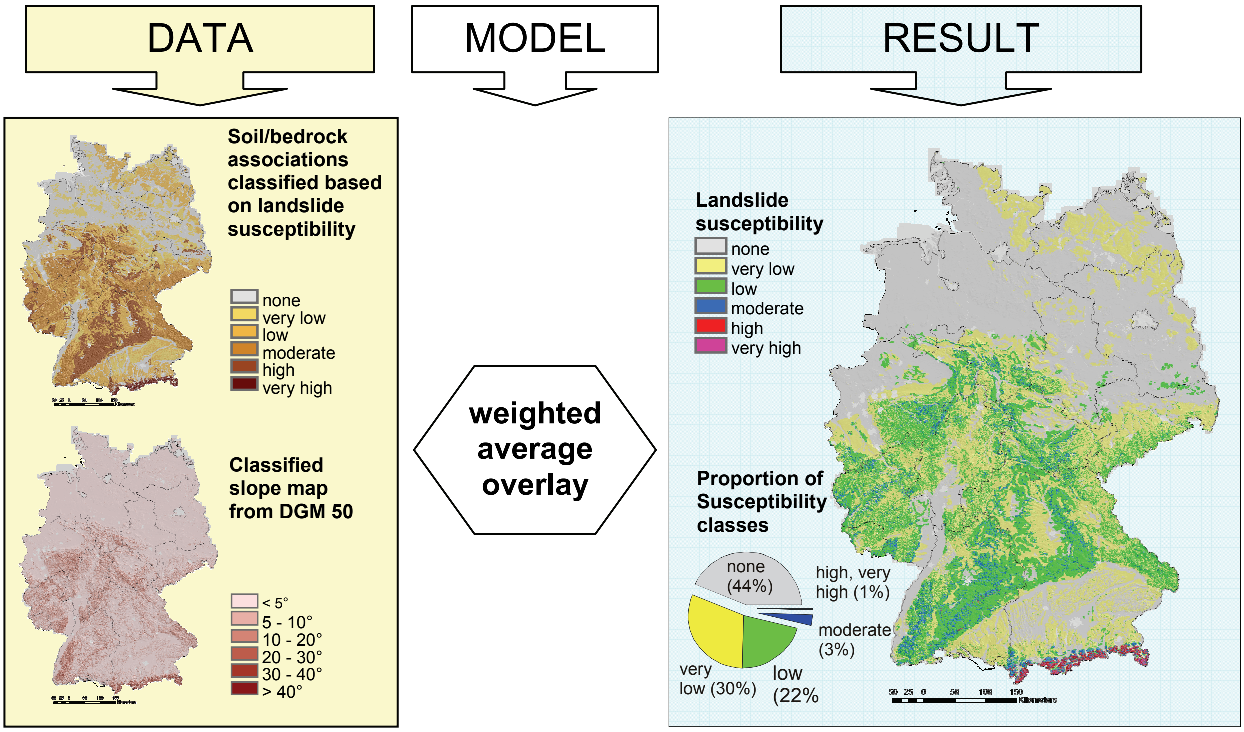

Figure 1: Heuristic landslide susceptibility model and map for Germany. The Figure shows thematic data used to ascertain landslide susceptibility, the adopted weighted overlay model, and the resulting susceptibility map. The susceptibility map has not been validated against landslide data.

The map shown in Fig. 1 portrays a qualitative zonation of landslide susceptibility in Germany, based on topographic and lithological/soil information. It is worth pointing out that no information on the location, type, or abundance of landslides was used to prepare the map. This is a limitation that should be considered when using the map. The geographical distribution of the susceptibility classes is in relatively good agreement with published field observations, and with the existing expert knowledge on landslides in Germany (see e.g. Glade and Crozier, 2005, and references therein). Visual inspection of the map reveals that areas classified as of moderate to very high susceptibility are located: (i) in the southernmost part of the country (e.g., in the Alpine region), where slopes are steep and landslide-prone soil/bedrock associations exist, (ii) along major, regional escarpments, (iii) along deeply incised rivers, and (iv) along the Baltic Sea coastal cliffs. Low to very low susceptibility classes extend in the hilly parts of the country, where soils are layered and slopes are gentle. Areas not susceptible to landslides correspond chiefly to flat areas. The map largely resembles an earlier qualitative landslide susceptibility map for Germany based on the heuristic analysis of a 1:1,000,000 scale geological map and topographic data prepared by Dikau and Glade (2003).

A similar susceptibility map can be prepared for Europe, because information on the ground conditioning factors (topography, and soil and bedrock properties) is available. It is a matter of debate if – or to what extent – other existing data on landslide conditioning and triggering factors (e.g., land cover, land use, climate, seismicity, etc.) should be used to prepare the European model of landslide susceptibility. To prepare the continent-wide landslide susceptibility model, we recommend using only a limited number of thematic factors. For preparing a heuristic landslide susceptibility model, expert agreement on appropriate scoring and weighting schemes for the thematic data used for the model is required. To improve the model, ground-conditioning factors should be re-classified to consider regional or local settings. It is important to evaluate and validate the obtained landslide susceptibility model with relevant landslide information available for different regions. Preparation of a European, heuristic landslide susceptibility model will represent a significant improvement with respect to the existing continental landslide hazard zonation map prepared by ESPON, i.e., the European Spatial Observation Network project (Schmidt-Thomé and Kallio, 2006).

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Criteria for the identification of landslide risk areas in Europe: the Tier 2 approach

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Establishing landslide hazard and risk for an entire nation is a difficult task and only a few, largely empirical, attempts have been pursued. The main difficulty to determine landslide susceptibility, hazard and to ascertain the associated risk for very large areas lies in the complexity and diversity of the landslide phenomena, and in the limited availability of relevant information for territories extending for hundreds of thousands of square kilometres (Chacón et al., 2006; Crozier and Glade, 2005; Guzzetti, 2006). At European level and according to the common criteria established by the Soil Information Working Group (SIWG) of the European Soil Bureau Network (ESBN), quantitative model-based (Tier 2) assessment of landslide susceptibility requires geographical information on landslides. According to the "tiered" approach for risk area delineations as proposed by SIWG (Eckelmann et al., 2006), quantitative inventory-based evaluations on landslide susceptibility should be conducted in areas identified as critical by the Tier 1 assessment. It is possible to perform quantitative evaluations of landslide susceptibility adopting statistical assessment techniques only where landslide inventory maps and/or associated databases are available.

In Italy, relevant information has become available to attempt a quantitative, nationwide (synoptic) assessment of landslide hazard and of the associated risk to the population. Preliminary to the definition of landslide hazard is the selection of an appropriate mapping unit. The municipality (an administrative and political subdivision) was selected as the terrain-partitioning unit. Italy is divided into 8103 municipalities, ranging in size from 0.11 km^2 (Atrani, Campania) to 1285 km^2 (Rome) (mean area = 37.3 km^2, mode = 26.3 km^2, std. dev. = 50.0 km^2). We prepared two hazard/risk models exploiting two catalogues listing historical information on damaging landslides and on landslides with human consequences in Italy. The two catalogues cover the 52-year period from 1950 to 2001 (Guzzetti and Tonelli, 2004). For modelling purposes, the catalogues were split in two sub-sets: (i) a training set, covering the 41-year period from 1950 to 1990, and (ii) a validation set, spanning the 11-year period between 1991 and 2001. The spatial probability of landslides (i.e., "where" landslides are expected) was obtained through multivariate analysis of synoptic thematic information (Fig. 1) (Guzzetti et al., 2005; Guzzetti et al., 2006), including lithological, soil and climate data, and a set of morphometric variables obtained from a 90 m × 90 m digital elevation model (DEM) acquired by the Shuttle Radar Topography Mission (SRTM) in February of 2000. Lithological information was obtained from a synoptic geological map published by Compagnoni and his collaborators in the period from 1976 to 1983. For the statistical analysis, the large number of rock units shown in the synoptic geological map (145 units) was grouped into 20 lithological types. Similarly, the 34 soil types shown in the synoptic soil map of Mancini (1966) were grouped into 8 classes of soil thickness and 11 classes of soil parent material. As the dependent variable, the presence or absence of damaging landslides (or of landslides that have resulted in casualties) in each municipality was used. To estimate the temporal probability of landslide occurrence (i.e., "when" or "how frequently" landslide events are expected), we first obtained an estimate of the average recurrence of landslide events in each municipality. Landslide event recurrence was obtained dividing the total number of damaging landslide events (or the total number of events with casualties) in each municipality by the time span of the investigated period (41 years). Next, the recurrence time of damaging landslide events (of landslide events with casualties) was assumed constant, and a Poisson probability model was selected to describe the temporal distribution of damaging landslide events (and of landslide events with casualties). Finally, the exceedance probability of having one or more damaging landslide event (or landslide event with casualties) in each municipality was computed for different periods, from 1 to 20 years. The temporal prediction models and the spatial prediction models were tested using independent landslide information, i.e., information not available to construct the models. Landslide validation sets covering the 11-year period between 1991 and 2001 were used to test the temporal models, the spatial models, and the joint hazard/risk models. Result of the model validation revealed that more than 70.0% of the landslides used as validation set occurred in municipalities classified as unstable (probability > 0.55). The validation revealed the ability of the model to predict where future landslides may occur in Italy.

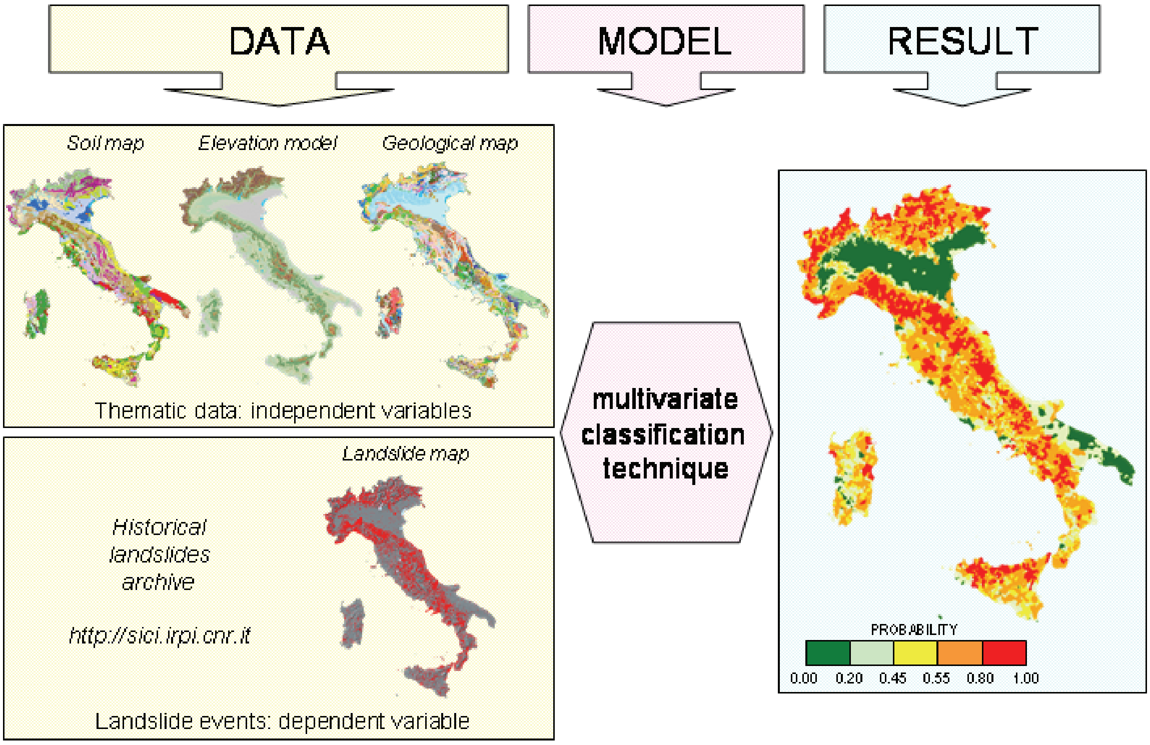

Figure 1: Probabilistic landslide susceptibility model for Italy. Figure shows the thematic and environmental data used to ascertain landslide susceptibility, the adopted statistical classification model, and the resulting susceptibility assessment. Probability of landslide spatial occurrence (susceptibility) is shown in 5 classes, from low (green) to high (red).

Combining the spatial and the temporal probability of damaging landslides and landslides with fatalities, we obtained two different models. The first model attempts to forecast the occurrence of all type of damaging landslides in Italy and is a type of hazard model (Fig. 2). The second model predicts the subset of damaging landslides that result in fatalities and can be used to estimate landslide risk to the population of Italy. Results of the hazard/risk modelling are shown using synoptic maps that portray landslide hazard/risk in the 8103 Italian municipalities in five probability classes, from very low to very high. The maps, albeit preliminary, are remarkable, and may be used by national and regional civil protection authorities, by national and regional environmental agencies, and by insurance and re-insurance companies to determine levels of landslide hazards and of landslide risk to the population of Italy.

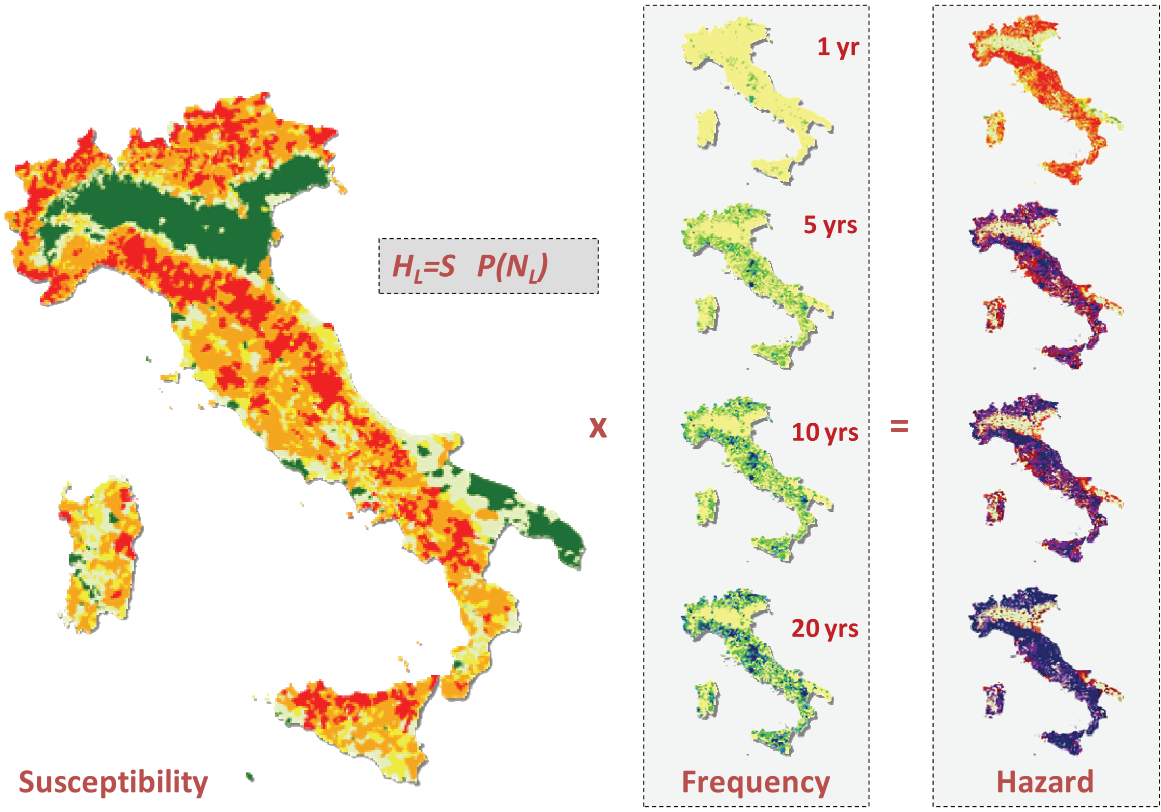

Figure 2: The figure shows a set of hazard scenarios obtained combing the susceptibility estimate of future damaging events with the exceedance probability for different time intervals.

Landslide hazard and risk models as proposed for Italy could be prepared for all the European nations whenever a landslide inventory map is or become available. To guarantee the comparability of the results throughout Europe, a standard on landslide inventories should be established, a suitable mapping unit should be discussed and quantitative landslide susceptibility evaluations should be carried out exploiting similar thematic information.

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Recommendations on a common approach for mapping areas at risk of landslides in Europe

European Landslides Expert Group

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Introduction

In order to identify landslide-prone areas in Europe using common approaches and thematic data where possible, as regarded in the European Union's Thematic Strategy for Soil Protection (EC, 2006a, 2006b), while accounting also for the different availability of geospatial, historical and other data of relevance to landslide mapping across Europe, the landslides expert group suggests to implement a multi-step mapping approach based on "Tiers" (Eckelmann et al., 2006; Günther et al., 2007; Reichenbach et al., 2007). This is basically a geographically nested approach ranging from small-scale to large-scale mapping, whereby areas identified as of higher susceptibility, hazard or risk in the initial Tier approach are mapped at larger scale and higher accuracy by successive Tiers. For Europe, three Tiers are suggested as follows.

Tier 1: Production of a European-wide heuristic landslide susceptibility map

In the first-step, Tier 1, a heuristic (i.e. expert knowledge-based) landslide susceptibility map is suggested to be produced for generic landslides (i.e. without differentiating landslide type) at 1:1,000,000 scale.

The main reason for selecting this particular scale is the free availability of the most important landslide conditioning and triggering factor data at least at such scale for the whole Europe. This could allow the use of harmonised data sets for all EU member states as input to the method/model to produce a consistent landslide susceptibility map across Europe. Since a coherent landslide inventory map or geospatial database does not exist at European level, a pan-European landslide susceptibility map can only be prepared without inventory data, e.g. through heuristic modelling using European-level landslide conditioning and, optionally, triggering data. Such a map will mainly show the areas susceptible to future landslides and their level of susceptibility. The latter is suggested to be represented as three classes, namely high, medium and low or nil.

Making a coherent landslide hazard map for the whole Europe, i.e. considering also "when or how frequently" landslides may occur, is regarded not feasible at the moment because of the frequent lack of historical records about the temporal occurrence of landslides in most countries.

The qualitative pan-European landslide susceptibility zonation map proposed will be used to delineate areas where quantitative, inventory-based Tier 2 landslide susceptibility evaluations must be conducted.

In order to produce the Tier 1 susceptibility map a minimum set of common landslide conditioning or preparatory factors was selected as follows:

- *Soil/parent material*, available at 1:1,000,000 scale from JRC's European Soil Data Centre – ESDAC (http://esdac.jrc.ec.europa.eu/). Use of the PAR-MAT-DOM dataset (dominant parent material of the soil typological units, STU) of the Soil Geographical Database of Eurasia (SGDBE) is recommended.
- *Slope angle*, to be derived mainly from NASA's SRTM DEM at 90m x 90m cell size.
- *Land cover*, now available from the Corine Land Cover dataset CLC2000, at 1:100,000 scale. A new dataset, CLC2006, is expected to be available from interpretation of 2006 satellite images by 2009, with improved resolution for land cover changes detected between the two datasets, although at the same representation scale as CLC2000.

In addition to these factors, the following landslide triggering factor data were selected either for a second run of the susceptibility assessment model outlined below or, more appropriately, for possible hazard mapping:

- *Climate: Precipitation*, which is available on a daily basis from JRC's MARS project at 50 km grid and from the EU FP5 PRUDENCE project (http://prudence.dmi.dk) at 12 km grid.
- *Seismic data*, available from the European earthquake catalogue.

For the input data to the model, a grid (raster) based mapping unit at 90m x 90m maximum resolution, as that provided by SRTM90 data should be used. Alternatively, coarser resolution data derived from those available could be considered.

The common susceptibility assessment approach recommended to be applied to each mapping unit consists of the following steps:

1. Each conditioning factor above is to be divided into classes, to which a relative weight will be given. To agree on this important task, it was recommended to have a dedicated meeting of experts from a wider range of member states.
2. Based on the decisions made, a first model will be parameterised and run. This will be based on global classifications and weighting / scoring of the input data.
3. The model will be tested with selected landslide inventory data available for France, Italy, Great Britain, Czech Republic and some Spanish regions (Andalusia, and possibly Catalonia and Cantabria), and possibly also for Sweden, so as to include a large sample of the various geologic materials and geomorphologic, climatic and seismic conditions existing in Europe.
4. As a result of the testing, the factor classes could be locally reclassified and the weighting schemata could be improved.
5. The model will be finally run and evaluated in each member state by an expert organization, preferably the national geological survey in coordination with EuroGeoSurveys.

The European landslide susceptibility map derived from the Tier 1 approach would thus phase out the current, less representative and incorrect ESPON landslide hazard map of Europe (Schmidt-Thomé, 2006). Whilst the experts group acknowledges the effort made and the constraints faced by the team that produced the ESPON map, it also feels that the mapping units then used (NUTS3) are generally too large and widely variable in size amongst member states. It further feels that the information provided by some national organizations in response to a questionnaire sent by the authors was either not adequate or simply missing. The ESPON map authors themselves recognize that NUTS 3 level is too coarse for pinpointing areas sensitive to landslides. As a result, large administrative units of up to more than 20,000 km^2 show an unrealistic uniform level of hazard on the one hand, whereas this level does not correspond to the actual one in many units on the other hand, hence rendering the map little reliable even at its very small representation scale.

European landslide inventory

It is recommended to carry out a pan-European landslide inventory, reviewing the data already available, both for validating Tier 1 and performing Tier 2 below. The minimum requirements for such an inventory are location and type of historical landslides. The landslide type classification should follow the one proposed by Varnes (1978). Additionally, the inventory should include date of occurrence, soil/bedrock material involved, surface extent and direct impact of landslide events (see Table 1).

Tier 2: Production of a quantitative landslide susceptibility map in landslide-prone regions delineated through Tier 1

It is recommended to generate a quantitative, inventory-based Tier 2 landslide susceptibility map in landslide-prone European regions delineated through Tier 1 at a scale in the order of 1:250,000. The precise scale is to be determined on the basis of the common base/thematic map scales used in member states. In order to produce this map, the following conditioning factors should be included:

- *Topographical attributes*, to be derived from SRTM and ASTER satellite data, unless higher resolution data across Europe (e.g. 10m cell size) is made available in the near to mid future.
- *Land cover*, now available at 1:100,000 scale from CLC2000 data and envisaged to be available at higher resolution, yet at the same scale, by 2009 from CLC2006 data (see above).
- *Bedrock and "engineering" soil types*, possibly including main geomechanical properties.
- *Major discontinuities*, especially faults. Fault activity classes could be established in connection with known earthquake activity and occurrence in Quaternary deposits.
- *Landslide occurrence*. The landslide inventory would include at least location (at 1:25,000 to 10,000 scale if represented as map polygons and at 1:200,000 to 1:100,000 scale if done as map points, see Table 1), type (from Varnes classification) and activity (e.g. active/dormant and relict, or active, inactive and unknown).
- Possibly *soil moisture regime*, which is more characteristic for the locality than momentary moisture.

For Tier 2, the mapping unit to be used is not yet fixed, but it is recommended to use municipalities or small catchments.

As suggested in Tier 1 for complementary susceptibility mapping or, alternatively, for hazard mapping, the following triggering factor data should be included:

- *Climate: Precipitation*, on a daily basis from high-resolution data as that provided by the PRUDENCE project (see above).
- *Seismic data*: Peak ground acceleration (PGA), possibly from ESPON's Global Seismic Hazard Assessment Project - GSHAP (Schmidt-Thomé, 2006).

The common susceptibility assessment method recommended to be applied to each mapping unit consists of two main steps:

1. Running a quantitative, multivariate statistical model for two or three types of landslides.
2. Validating and evaluating the model using landslide event maps where available.

Generation of Tier 3 landslide susceptibility maps in local, highly-prone landslide areas

It is further considered the possibility to implement a Tier 3 approach in high susceptibility areas identified by the Tier 2 approach. Should Tier 3 assessments be implemented, it is recommended to apply physically-based models for different types of landslide phenomena if geotechnical data (e.g. main soil/bedrock and hydraulic properties) are already available or planned to be collected. A tentative scale for this modelling could be in the order of 1:10,000 (see Table 1).

Table 1: Main landslide inventory data specifications for proposed Tier-based maps. Tier 3 has been further divided into two possible sublevels, 3a and 3b.

MAP	Tier 1 (1:1,000,000)		Tier 2 (1:250,000)		Tier 3a (1:25,000)	Tier 3b (1:10,000)
Methodology for susceptibility	Heuristic, weighted factors		Probabilistic, quantitative bivariate or multivariate		Probabilistic, quantitative multivariate	Deterministic, physical models
Inventory scale	1:200,000		1:50,000		1:10,000	1:10,000-1:2000
Inventory geometry	Points	Polygons	Points	Polygons	Polygons	Polygons
Landslide size	1 – 5 Ha	> 5 Ha	500 – 2500 m^2	> 2500 m^2	> 100 m^2	any
Information in the inventory	At least landslide location and type		At least landslide location, type and activity		Full database information	

Finally, complementary issues regarding map harmonization, such as the use of metadata standards, interoperability including also common data exchange formats, data accessibility and other specifications, have not been yet dealt with by the experts group. In general they have to be compliant with the INSPIRE Directive (EC, 2007).

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Abstract

In the framework of the EU Thematic Strategy for Soil Protection and the associated Proposal for a Soil Framework Directive, landslides are included as one of the soil threats for which it is necessary to identify the areas at risk in EU member states and implement national mitigation programmes. In this context, this publication presents the results of a meeting of experts from a number of national geological surveys, research institutes and universities in Europe, held at the Joint Research Centre (JRC) in Ispra, Italy on 23-24 October 2007, with the main aim to discuss and draft guidelines for mapping areas at risk of landslides in Europe. This volume includes examples of landslide inventories and susceptibility, hazard and risk mapping approaches in France, Germany, Great Britain, Greece, Italy and Spain. It also discusses some harmonisation issues and criteria for mapping landslide susceptibility across Europe. In addition, it draws recommendations on a common methodology for landslide susceptibility mapping based on geographically-nested "Tier" approaches at various scales, from European-wide, small-scale mapping using heuristic methods and readily available data on landslide conditioning and triggering factors, to medium-scale mapping by statistical approaches using also landslide inventory data, and to large-scale susceptibility assessment applying physically-based models in high-risk local areas pinpointed by the previous Tier approaches.

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